PB-240 005

DEMONSTRATION OF A HIGH-RATE ACTIVATED SLUDGE SYSTEM

Elmer L. Miller

Engineering-Science, Incorporated

Prepared for:

National Environmental Research Center

March 1975

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-670/2-75-037	2. PB 240 005
4. TITLE AND SUBTITLE DEMONSTRATION OF A HIGH-RATE ACTIVATED SLUDGE SYSTEM	5. REPORT DATE March 1975-Issuing Date 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Ching H. Huang,† Donald L. Feuerstein,† and Elmer L. Miller‡	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS †Engineering-Science, Inc.,Berkeley, California 94710 ‡City of Chino, Chino,California 91710	10. PROGRAM ELEMENT NO. 1BB043 ROAP 21ASR, Task 007 11. CONTRACT/GRANT NO. WPRD 16-01-67
12. SPONSORING AGENCY NAME AND ADDRESS National Environmental Research Center Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES	

Reproduced by NATIONAL TECHNICAL INFORMATION SERVICE US Department of Commerce Springfield, VA. 22151

16. ABSTRACT

A high-rate activated sludge system was designed, constructed and operated at the City of Chino as a biological treatment system utilizing the maximum growth-rate potential of activated sludge as a means of removing organic, and possibly inorganic, materials from domestic wastewater.

Operating results indicate that full-scale systems can be operated at high growth rates and high substrate loading rates with concomitant high substrate removal velocities and high quality effluent. Substrate loading rates as high as 3.6 (mg BOD)/(mg MLVSS)(day) and effluent BOD as low as 5 mg/l were achieved.

A kinetic description indicated a yield coefficient of 0.92 (mg MLVSS produced)/(mg BOD removed), a decay constant of 0.027 day^{-1} and a half-saturation constant of 26 (mg BOD)/l. The significance of these kinetic characteristics in process design and operational control is presented.

Four solids separation systems--vibratory screens, enhanced gravity separation, dissolved air flotation and hydro-centrifugal cleaned screens--were tested for activated sludge solids separation. Vibratory screens were not effective for separation of high-rate activated sludge solids under the operating conditions employed during this study. Enhanced gravity separators, however, were effective for separation of high-rate activated sludge solids, but only at very low operating overflow rates.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Sludge, *Sewage, *Activated sludge process, *Sewage treatment, Waste water, Sewage filtration, Separation, Biochemical oxygen demand, Reaction kinetics, Sewage disposal	High-rate activated sludge system, Chino (California), Solids separation, Biological kinetics	13B

PRICES SUBJECT TO CHANGE

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 151
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE $6.25-2.25

078112

PB 240005
EPA-670/2-75-037
March 1975

DEMONSTRATION OF A HIGH-RATE ACTIVATED SLUDGE SYSTEM

By

Ching H. Huang
Donald L. Feuerstein
Engineering-Science, Inc.
Berkeley, California 94710

and

Elmer L. Miller
City of Chino
Chino, California 91710

Grant No. WPRD 16-01-67
Program Element No. 1BB043

Project Officer

Gerald Stern
Advanced Waste Treatment Research Laboratory
National Environmental Research Center
Cincinnati, Ohio 45268

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. Department of Commerce
Springfield, VA. 22151

NATIONAL ENVIRONMENTAL RESEARCH CENTER
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

REVIEW NOTICE

The National Environmental Research Center--Cincinnati has reviewed this report and approved its publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effect of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

As part of these activities, the study described herein presents an investigation to determine the feasibility of using a high-rate biological system for treating municipal wastewater at lower costs while still maintaining effluent quality standards, with possible reuse of the treated wastewater for recreational purposes.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

An optimum performance activated sludge system, comprised of an accelerated high-rate activated sludge process and associated solids separation processes, was designed, constructed and operated at the City of Chino as a biological treatment system utilizing the maximum growth-rate potential of activated sludge as a means of removing organic, and possibly inorganic nutrient, materials from domestic wastewater.

Operating results from this investigation indicate that full-scale systems can be operated at high growth rates and high substrate loading rates with concomitant high substrate removal velocities and high quality effluent. Substrate loading rates as high as 3.6 (mg BOD)/(mg MLVSS) (day) and effluent BOD of as low as 5 mg/l were achieved.

A kinetic description of this activated sludge system indicated a yield coefficient of 0.92 (mg MLVSS produced)/(mg BOD removed), a decay constant of 0.027 day^{-1} based on BOD, a maximum substrate removal velocity of 4.1 (mg BOD removed)/(mg MLVSS)(day), a maximum specific growth rate of 3.8 day^{-1}, and a half-saturation constant of 26 (mg BOD)/l. The significance of these kinetic characteristics in process design and operational control is presented.

Four solids separation systems, *viz.*, vibratory screens, enhanced gravity separation, dissolved air flotation and hydro-centrifugal cleaned screens, were tested for activated sludge solids separation. Vibratory screens were not effective for the separation of high-rate activated sludge solids under the operating conditions employed during this study. Enhanced gravity separators were effective for the separation of high-rate activated sludge solids, but only at very low operating overflow rates.

If advantage is to be taken of the substrate removal capabilities of high-rate activated sludge systems, a greater effort in the development of improved mechanical solids separators is indicated.

This report was submitted in fulfillment of Project Number 17050 DZE Grant No. WPRD-16-01-67, by the City of Chino, California, under the partial sponsorship of the U.S. Environmental Protection Agency. Work was completed as of August 1974.

CONTENTS

		Page
Foreward		iii
Abstract		iv
List of Figures		vii
List of Tables		ix
Acknowledgments		xi
Sections		
I	Conclusions	1
II	Recommendations	5
III	Introduction	6
IV	Activated Sludge Process Description	8
V	Theory and Rationale	12
VI	Experimental Procedure and Analytical Method	29
VII	Results and Discussion	42
VIII	Design and Operational Implications	126
IX	Glossary	133
X	References	134
XI	Appendix	138

FIGURES

No.		Page
1	Completely mixed activated sludge process	14
2	Michaelis-Menten (Monod) kinetic model	17
3	Water reclamation facilities of City of Chino	30
4	Plot of cell continuity equation using BOD as substrate parameter	62
5	Plot of cell continuity using COD as substrate parameter	63
6	Cell continuity equation for mean steady-state values using BOD as substrate parameter	65
7	Cell continuity equation for mean steady-state values using COD as substrate parameter	66
8	Plot of cell continuity equation using BOD and ATP	67
9	Plot of cell continuity equation using COD and ATP	68
10	Plot of cell continuity equation using BOD and dehydrogenase activity	69
11	Plot of cell continuity equation using COD and dehydrogenase activity	70
12	Plot of Michaelis-Menten (Monod) equation for accelerated high-rate activated sludge system using BOD as substrate parameter	73
13	Plot of Michaelis-Menten (Monod) equation using BOD and ATP	74
14	Plot of Michaelis-Menten (Monod) equation using BOD and dehydrogenase activity	76
15	Plot of modified Michaelis-Menten (Monod) equation for accelerated high-rate activated sludge system using COD as substrate parameter	77
16	Plot of modified Michaelis-Menten (Monod) equation using COD and ATP	78
17	Plot of modified Michaelis-Menten (Monod) equation using COD and dehydrogenase activity	79

FIGURES (Continued)

No.		Page
18	Relationship between oxygen transfer rate and BOD removal velocity	95
19	Estimated oxygen transfer rate and COD removal velocity	96
20	Effect of organic loading velocity on sludge volume index	112
21	Hydraulic capacity of vibratory 0.044-mm opening (325-mesh) screen	117
22	Hydraulic capacity of vibratory 0.037-mm opening (400-mesh) screen	118
23	Hydraulic capacity of vibratory 0.014- by 0.105-mm opening (720- by 140-mesh) screen	119
24	Effect of surface loading on gravity settler performance	122
25	Effect of cell age on gravity settler performance	123

TABLES

No.		Page
1	Process Monitoring Characteristics and Daily Routine Laboratory Analyses	37
2	Primary Effluent Wastewater Characterization	43
3	Summary of Primary Effluent Wastewater Characterization	47
4	Mean Values of Steady-State Performance Parameters	49
5	Summary of Steady-State Measurements	51
6	Summary of Steady-State Performance Parameters	54
7	Steady-State Active Organism Concentration Measurements	58
8	Steady-State Performance Characteristics Based on ATP and Dehydrogenase Activity	60
9	Evaluation of Cell Continuity Equation Using ATP and Dehydrogenase Activity as Active Biomass Parameters	81
10	Evaluation of Michaelis-Menten (Monod) Equation Using ATP and Dehydrogenase Activity As Active Biomass Parameters	82
11	Summary of Most Probable Kinetic Growth Constants of Accelerated High-Rate Activated Sludge System	83
12	Activated Sludge Process Kinetic Constants	84
13	Oxygen Transfer Kinetic Constants in Aerobic Biological Processes	89
14	Oxygen Transfer Kinetic Data and Sludge Volume Index	91
15	Steady-State Nitrogen and Phosphorus Concentrations	98
16	Average Nitrogen and Phosphorus Concentrations in Primary and Secondary Effluents	102
17	Nutrient Removal Velocities and Removal Efficiencies	104

TABLES (continued)

No.		Page
18	Vibratory Screen Performance Data	114
19	Summary of Vibratory Screen Performance	116
20	Gravity Settler Performance	121
21	Design and Operational Parameters for Activated Sludge Processes	129
22	Design Comparison Between Conventional and High-Rate Chino Activated Sludge Processes	131

ACKNOWLEDGMENTS

The following key individuals from the City of Chino were responsible for implementation and conduct of the project: Mr. John R. Wright, City Administrator; Mr. Elmer Miller, City Engineer; Mr. James Diaz, Finance Officer; Mr. Arthur Hern, Manager of City Services; Mr. James Estrada, Chief Operator; and Mr. Tibaldo Canez, Chief Chemist.

The assistance of Mr. Gerald Stern, EPA Project Officer, is gratefully acknowledged.

Participants from Engineering-Science, Inc. in the project were Mr. Kline P. Barney, who served as Project Manager during the initial and data acquisition phases of the study. Dr. Donald L. Feuerstein replaced Mr. Barney as Project Manager during the data evaluation and report preparation phases of the project. Mr. Arthur S. Anderson served as Project Engineer and was responsible for the performance of the project during the development and acquisition of all field and laboratory results. Dr. Ching H. Huang evaluated the data and results and prepared the final report.

Dr. Erman A. Pearson acted as special consultant on the project.

SECTION I

CONCLUSIONS

This investigation has yielded quantitative kinetic descriptions of a full-scale activated sludge plant, which include growth rates, decay rate constants, yield coefficients and other kinetic coefficients and constants. Results from this investigation indicate that plant-scale systems can be operated at high growth rates and high substrate loading rates with concomitant high substrate removal velocities and high quality effluent. Substrate loading rates as great as 3.6 (mg BOD)/(mg MLVSS)(day), substrate removal velocities as large as 3.2 (mg soluble BOD removed)/(mg MLVSS)(day) and effluent soluble BOD concentrations as low as 5 mg/l were observed during this study. Based on this investigation, a number of specific findings and conclusions are presented.

KINETIC CHARACTERIZATION OF ACCELERATED HIGH-RATE ACTIVATED SLUDGE SYSTEMS

The activated sludge process was operated as a very low-rate system, *viz.*, average growth rate of 0.035 day^{-1}, or as a very high-rate system, *viz*, average growth rate of 2.16 day^{-1}. Optimum BOD loadings on an activated sludge system with gravity cell separation appear to be in the range of 2.0 to 3.6 (mg BOD)/(mg MLVSS)(day).

The cell continuity equation, $1/\theta_c = Yq - k_d$, and the Michaelis-Menten (Monod) equation, $\mu = \hat{\mu}S_1/(K_s + S_1)$, were used to describe kinetic characteristics of the accelerated high-rate activated sludge system, and system kinetic coefficients and constants were developed.

Kinetic analysis of data from the full range of substrate loading rates employed in this study, *viz*, 0.137 to 3.64 (mg BOD)/(mg MLVSS)(day), suggests the following kinetic coefficients and constants for the accelerated high-rate activated sludge system:

Kinetic Constants	Substrate Parameter: BOD	COD
Yield coefficient, Y	0.92 $\frac{\text{(mg MLVSS)}}{\text{(mg BOD)}}$	0.33 $\frac{\text{(mg MLVSS)}}{\text{(mg COD)}}$
Decay constant, k_d	0.027 day^{-1}	-0.023 day^{-1}
Maximum substrate removal velocity, $\hat{q}$	4.1 $\frac{\text{(mg BOD)}}{\text{(mg MLVSS)(day)}}$	8.4 $\frac{\text{(mg COD)}}{\text{(mg MLVSS)(day)}}$
Maximum specific growth rate, $\hat{\mu}$	3.8 day^{-1}	2.7 day^{-1}
Half-saturation constant, K_s	26 mg/l	95 mg/l
Nonbiodegradable substrate concentration, K_{COD}	-	20 mg/l

The usefulness of kinetically describing accelerated high-rate activated sludge systems using ATP and dehydrogenase activity as active biomass parameters was not documented due to the high variance of the limited data obtained.

The relatively low values of the half-saturation constants, K_{sBOD} = 26 mg/l and K_{sCOD} = 95 mg/l, indicate that both BOD and COD are adequate substrate parameters; and the organic substrate concentration expressed as either BOD or COD was the rate-limiting factor in the accelerated high-rate activated sludge system.

Least-square analysis suggests the following values of constants in the oxygen requirements equation, $U = aqX_1 + bk_dX_1$, assuming that the oxygen transfer capacity for the EIMCO-SIMCAR aerator was 1.22 (kg O_2 transferred)/(kw-hr consumed) [2.0 lb/(hp-hr)]:

Aeration Constants	Substrate Parameter	
	BOD	COD
a	$0.438 \frac{(mg\ O_2)}{(mg\ BOD)}$	$0.174 \frac{(mg\ O_2)}{(mg\ COD)}$
bk_d	$0.432 \frac{(mg\ O_2)}{(mg\ MLVSS)(day)}$	$0.414 \frac{(mg\ O_2)}{(mg\ MLVSS)(day)}$

NUTRIENT REQUIREMENTS AND REMOVAL

A minor degree of nitrification took place in the accelerated high-rate activated sludge system as the nitrite plus nitrate increased on the average from 0.08 mg/l as N in the influent to 0.90 mg/l as N in the effluent.

The net yield coefficients, Y_n, with respect to specific nutrients, obtained from data representing a wide range of substrate loading rates, *viz*, 0.137 to 3.64 (mg BOD)/(mg MLVSS)(day), were found to be 11.3 (mg MLVSS produced)/(mg Kjeldahl nitrogen removed), 20.1 (mg MLVSS produced)/(mg ammonia removed), 14.4 (mg MLVSS produced)/(mg total dissolved phosphate as P removed) and 28.5 (mg MLVSS produced)/(mg dissolved orthophosphate as P removed).

Based on cell yield coefficient and the quantities of nitrogen and phosphorus requirements of the activated sludge determined in this study, the nutrient requirements were estimated to be 112 (mg N)/(g BOD removed) and 33 (mg P)/(g BOD removed) as compared to the most commonly reported values of 40 (mg N)/(g BOD removed) and 6 (mg P)/(g BOD removed).

The Michaelis-Menten (Monod) model for nitrogen and phosphorus removals could not be used because of the high concentrations of these constituents in the primary effluent and the very small removals that were effected in the activated sludge process.

SOLIDS SEPARATION SYSTEMS

Only about 10 percent of the applied hydraulic loading, which ranged between 8.4 and 24.4 $m^3/(m^2)(day)$ [200 and 600 $gal/(ft^2)(day)$], passed through the vibratory screen with a 0.014- by 0.105-mm opening (720-by 140-mesh) at solids loading rates of less than 97.9 $kg/(m^2)(day)$ [20 $lb/(ft^2)(day)$]. These filtration rates are too low in comparison to gravity settlers.

The three vibrating screens with 0.044-mm opening (325-mesh), 0.037-mm opening (400-mesh) and 0.014- by 0.105-mm opening (720- by 140-mesh) removed 38, 49 and 91 percent of mixed liquor suspended solids. on the average, respectively. Solids removal was low in all but the smallest size screen, but even the highest solids removal does not compare with the 95 to 99 percent solids removal achieved with a gravity settler operating at an overflow rate of about 12.2 $m^3/(m^2)(day)$ [300 $gal/(ft^2)(day)$].

No solids separation data were obtained on the gravity settlers at conventional secondary clarifier overflow rates, *i.e.*, about 32.6 $m^3/(m^2)(day)$ [800 $gal/(ft^2)(day)$], but gravity settlers were effective in separating high-rate activated sludge mixed liquor suspended solids at overflow rates of about 12.2 $m^3/(m^2)(day)$ [300 $gal/(ft^2)(day)$].

SECTION II

RECOMMENDATIONS

Based on the results and conclusions reported herein, the following recommendations are offered:

Kinetic descriptions of the biological process should be developed for all activated sludge plants to provide a rational and accurate basis for process design and operational control to achieve a specified effluent quality. To permit development of kinetic data, all activated sludge plants should have flow meters located on the aerator influent, return sludge and waste sludge lines and continuous proportional samplers located on the raw sewage, primary effluent (aerator influent), aerator effluent and return sludge and final plant effluent lines.

A better measure of the active solids content of the activated sludge for description of activated sludge growth kinetics than the mixed liquor volatile suspended solids (MLVSS), adenosine triphosphate (ATP) or dehydrogenase activity needs to be developed.

If advantage is to be taken of the substrate (pollutant) removal capabilities of high-rate activated sludge systems, increased effort should be devoted to the development of more efficient secondary cell separators.

Because only about one year was funded under this demonstration grant for operation of the demonstration process, more time and effort is needed to investigate process kinetics and, particularly, potentially better solids separation systems. Time and funds permitted only a small part of the scope of work plan to be completed.

SECTION III

INTRODUCTION

Biological waste treatment systems are currently the most widely used method of removing organic materials from municipal and industrial wastewaters. The most versatile and efficient of the available biological processes is the activated sludge system in which flocculated biological growths are continuously circulated and contacted with primary effluent in an aerated environment and then separated from the treated wastewater by sedimentation.

Utilization of the maximum growth-rate potential of the activated sludge process is proposed for removing organic materials from wastewater, at potentially lower costs if the active biological cells, or solids, can be separated effectively from the effluent liquid. A maximum growth-rate system could result in relatively small treatment plants which can be constructed at significantly lower costs.

Based on this approach, the City of Chino was provided a grant by the U.S. Environmental Protection Agency to demonstrate the feasibility of an optimum performance activated sludge system, comprised of an accelerated high-rate activated sludge process and associated solid separation processes as a wastewater treatment system for the removal of organic and nutrient materials. This project served two needs: it provided the City of Chino with a badly needed waste treatment facility and it provided technical information to the U.S. Environmental Protection Agency.

OBJECTIVES

The general objective of the study was the development of an optimum performance high-rate activated sludge system and the kinetic characteristics of the proposed process. Specific objectives were:

(1) To describe the process by kinetic analysis which would provide a more rational basis for design and operation of the activated sludge process;

(2) To determine the process kinetic characteristics, *e.g.*, maximum growth rate, decay rate constant, yield coefficient and half-saturation constant, with respect to system performance parameters;

(3) To delineate the nutrient, *i.e.*, nitrogen and phosphorus, removal as a function of the process operating parameters;

(4) To evaluate the performance of alternative mixed liquor solids separation systems, such as enhanced gravity sedimentation, vibratory screens, dissolved air flotation and pressurized hydro-centrifugal screening; and

(5) To determine the suitability of using the plant effluent from a high-rate activated sludge process for recreational purposes.

CONDUCT

This project was conducted in compliance with the requirements of the agreement between the City of Chino and the U.S. Environmental Protection Agency under the Grant No. WPRD 16-01-67.

The design and construction of the demonstration activated sludge plant was completed in 1970. The demonstration plant was operated for 15 months, extending from October 1970 to January 1972.

Throughout the grant period, Engineering-Science, Inc. served in the role of design engineers and provided the project engineers for plant operation and documentation.

SECTION IV

ACTIVATED SLUDGE PROCESS DESCRIPTION

The activated sludge process can be defined as a system in which the flocculated biological growths are continuously circulated and contacted with organic wastewater in the presence of oxygen. The system involves an aeration step followed by a solid-liquid separation step, from which most of the separated sludge is recycled back for mixture with the wastewater and the remainder is wasted (waste activated sludge). Biological synthesis, respiration, oxidation, flocculation and solids separation are the five subprocesses which constitute the activated sludge process. The activated sludge process is very flexible and can be adapted to almost any type of biological waste treatment problem. Many modifications of activated sludge process have been developed. The various modifications in use today are conventional, complete-mixed, step-aeration, modified aeration, contact-stabilization, extended aeration, Kraus process, high-rate aeration and pure-oxygen systems.

OPTIMUM PERFORMANCE ACTIVATED SLUDGE PROCESS

The optimum performance activated sludge process consists of an accelerated high-rate activated sludge unit and associated solids separation units. The concept of this proposed process recognizes that there are two forms of substrate in wastewater--soluble substances and colloidal-suspended material. Colloidal-suspended material can be removed effectively by solids separation systems which utilize flocculation as a precursor to separation. The soluble fraction can be removed by biosorption, biosynthesis and biological oxidation in aeration tanks.

Recognizing that uptake of soluble substrate by bacterial cultures can be very rapid, it is realized that extremely high-rate activated sludge processes could be constructed if a solids separation system capable of removing the bacteria and colloidal-suspended matter could be developed.

Current activated sludge systems rely on flocculent bacterial cultures for removal of both soluble and insoluble forms of substrate. The optimum performance activated sludge process relies on the active bacterial culture for rapid uptake of soluble substrate and the adsorption of colloidal matter on the active biological mass with an improved solids separation system. The potential advantage of this system includes the application of higher organic loadings, which results in plant size reductions and concomitant reductions in construction costs.

SOLIDS SEPARATION PROCESSES

Separation of the biological cells (solids) from the treated wastewater is the objective of the second phase of the activated sludge process. In traditional forms of the activated sludge process, the biological reactor is operated in a manner which produces a sludge which is readily settleable in a separator. The close coupling of the biological reactor and the separator makes the performance of these units interdependent.

All solids separation devices can be classified into two distinct types, gravimetric separators and solids restraining devices. The gravimetric separation devices include the separators in which solids are transported through the liquid either by gravity, centrifugal force or static electrical force. The solids restraining separators include all devices in which solids are retained on media upon passage of the liquid. The media can be of a fixed nature such as screens, fabrics, papers and membranes or of a nonfixed configuration like granular media.

Gravity sedimentation is the principle method of solids separation used in the activated sludge process because to date it has the best cost/effectiveness ratio. Therefore, the production of settleable sludge

is one of the primary requirements for the activated sludge process. However, gravity sedimentation for the final step in the activated sludge process has several fundamental disadvantages which are:

(1) The inability to separate sludges effectively having specific gravities near that of the liquid;

(2) The inability to concentrate filamentous sludges, which have poor settling characteristics;

(3) The practical inability to remove by gravity sedimentation particles as small as the size of cellular particles that one would like to remove; and

(4) The instability of the activated sludge process caused by uncontrollable variations in particulate solids (cells plus detritus) characteristics and the inherent variations in the hydraulic characteristics of sedimentation basins.

All of these process limitations can be tolerated if it is not necessary to produce a consistently high quality effluent. However, increasing performance standards are forcing designers to re-examine the process as a whole and to focus on the process rate-limiting step of final solid-liquid separation (sedimentation).

Much work has been done to improve operation of biological reactors to minimize solids separation problems associated with variable sludge characteristics. Organic and inorganic sludge conditioners have been used to increase the size of particles thus improving solids flocculation and to increase floc strength, and thereby making them less susceptible to disaggregation due to hydraulic transient shear. Some workers have focused attention on the problem of hydraulic short circuiting and its effect on solid-liquid separation. This work has led to the development of a number of stilling devices which include tube settlers, lamella settlers and tray settlers. Moreover, some designers have added a filtration process downstream of the biological process to meet more stringent water quality requirements.

Development of improved solid separation systems which are better suited to the variable characteristics requirements of biological processes is needed if maximum use is to be made of biological removal mechanisms.

SECTION V

THEORY AND RATIONALE

Significant progress has been made in the practical application of biological systems to municipal and industrial wastewater treatment. However, most of the progress in waste treatment technology has been the result of field experimentation, largely on a trial and error basis. Much of the research in waste treatment has been devoted to the development of rational or semi-rational explanations of the phenomena observed in practice.

The objective of biological waste treatment, namely the removal of organic materials from the wastewater, usually expressed in terms of biochemical oxygen demand (BOD) or chemical oxygen demand (COD), is the major consideration of kinetic analysis. Moreover, the activated sludge process can be used to remove from the wastewater stream some of the essential nutrients, such as nitrogen and phosphorus, by incorporation in cell tissue. The proper kinetic descriptions of substrate and nutrient removals should provide a rational basis for the analysis and design of activated sludge systems.

PRINCIPAL REACTOR TYPES AND FLOW CHARACTERISTICS

Most biological treatment processes utilized in wastewater treatment are designed to take place in continuous-flow systems. Since such processes are time dependent, the hydraulic residence time and the mixing characteristics of the systems are of vital importance. The actual mixing characteristics vary with the design of the system and are too complex to be described precisely. For this reason, use is made of simple flow models in estimating these characteristics.

There are three major types of biological system models, classified in terms of flow condition and mixing characteristics, which are commonly used in the activated sludge process.

Plug-Flow Reactor

In a plug-flow reactor, each element of the flowing mass follows another in sequence as though separated from it. Consequently, there is no longitudinal mixing between the elements although there may be lateral or radial mixing within each element. Each element is in the system for a time equal to the theoretical retention time. This type of flow would be approximated in a long pipe having a relatively small cross section.

Continuous-Flow, Stirred-Tank Reactor

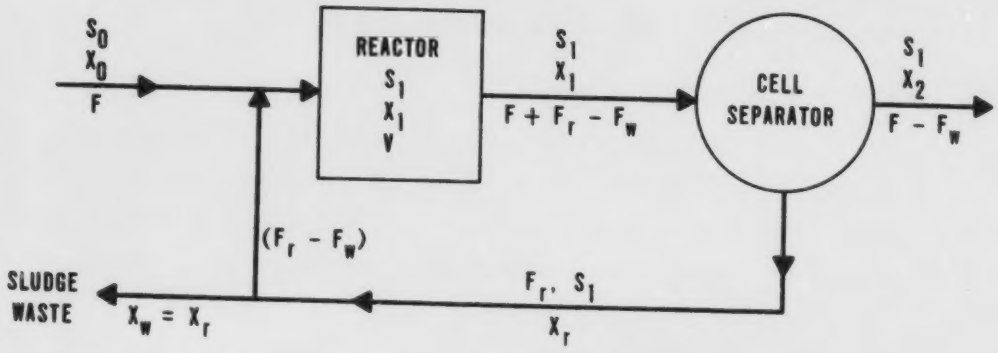
A continuous-flow, stirred-tank reactor is a simple homogeneous system consisting of a stirred tank into which influent wastewater is fed and intermixed immediately with contents of the reactor. The liquid in the reactor is completely mixed so that its properties are uniform and identical with those of the effluent. Thus, at a steady-state condition, the substrate level and physiological conditions of the cells in the reactor are maintained throughout the reactor at a constant level.

Arbitrary-Flow Reactor

Arbitrary-flow represents any degree of partial mixing between plug and completely-mixed flow. This type of flow is encountered frequently in actual aeration tanks and is difficult to describe mathematically. Therefore, in the kinetic analysis of arbitrary-flow reactors, plug-flow or completely-mixed flow models are usually assumed.

KINETICS OF COMPLETELY-MIXED ACTIVATED SLUDGE PROCESS

The completely-mixed process, schematically depicted in Figure 1, is characterized by a series of systems of constant volume, being as a whole in a dynamic steady-state condition with essentially constant concentrations of organic substrates and of activated sludge in the system.



F = Influent flow rate

F_r = Return activated sludge flow rate

F_w = Waste activated sludge flow rate

X_0 = Influent cell concentration

X_1 = Mixed liquor cell concentration

X_2 = Effluent cell concentration

X_r = Return activated sludge cell concentration

S_0 = Influent substrate concentration

S_1 = Effluent substrate concentration

V = Volume of aeration tank

X_w = Waste activated sludge cell concentration

Figure 1 Completely mixed activated sludge process

Continuous-flow, completely-mixed system cultivation permits determination of process kinetics and parameters which can be used both in theoretical analysis and in practical system design.

Basic Assumptions

To develop rationally a mathematical model for a continuous-flow, completely-mixed system, two basic assumptions are made:

(1) The specific growth rate of organisms in the reactor is some function of the rate-limiting substrate concentration, thus

$$\mu = \frac{1}{X} \frac{dX}{dt} = f(S) \qquad (1)$$

where X = concentration of activated sludge

μ = specific growth rate

S = concentration of organic substrate.

(2) The specific growth rate of the organisms varies with the rate of consumption of the limiting organic substrate, namely

$$\frac{dX}{dt} = - Y \frac{dS}{dt} \qquad (2)$$

where Y = yield coefficient.

It is generally assumed that the yield coefficient, Y, is a process kinetic constant.

Monod Model (Michaelis-Menten Equation)

The most widely accepted model for expressing the relationship between specific growth rate and substrate concentration is the rectangular hyperbola. This relationship has a theoretical basis in the Michaelis-Menten equation which was developed to describe the rate of an enzyme reaction as a function of substrate concentration (Reference 1), as well as an empirical basis as proposed by Monod (References 2 and 3) to describe the relationship between bacterial growth rate and substrate concentration.

It takes the form,

$$\mu = \hat{\mu}\left(\frac{S}{K_s + S}\right) \qquad (3)$$

where $\hat{\mu}$ = maximum specific growth rate

K_s = half-saturation constant, numerically equal to the substrate concentration at which the specific growth rate is one-half the maximum growth rate, *i.e.*, $\mu = \hat{\mu}/2$.

The Michaelis-Menten (Monod) kinetic model for describing the relationship between the growth rate and substrate concentration, shown in Figure 2, has been widely used by microbiologists and engineers working with continuous culture systems (References 4, 5, 6, 7 and 8).

Kinetics of Activated Sludge Process

In developing the process kinetics of the activated sludge system with cell recycle, continuity of biomass and substrates in steady-state condition are maintained.

Materials Balance for Cell Biomass--

One of the important characteristics of the activated sludge system is cellular recycle and the controlled wasting rates of sludge produced during treatment. This permits control of the cell concentration and effluent quality over considerable limits. For a continuous-flow, stirred-tank reactor with cell recycle, a materials balance for the entire process is expressed by the following equation:

[rate of change of cell biomass in the reactor] = [rate of input of cells] - [rate of output of cells] + [growth rate of cells] - [decay rate of cells]

or

$$V\frac{dX_1}{dt} = FX_0 - (F - F_w)X_2 - F_wX_r + \mu X_1V - k_dX_1V \qquad (4)$$

where k_d = decay rate.

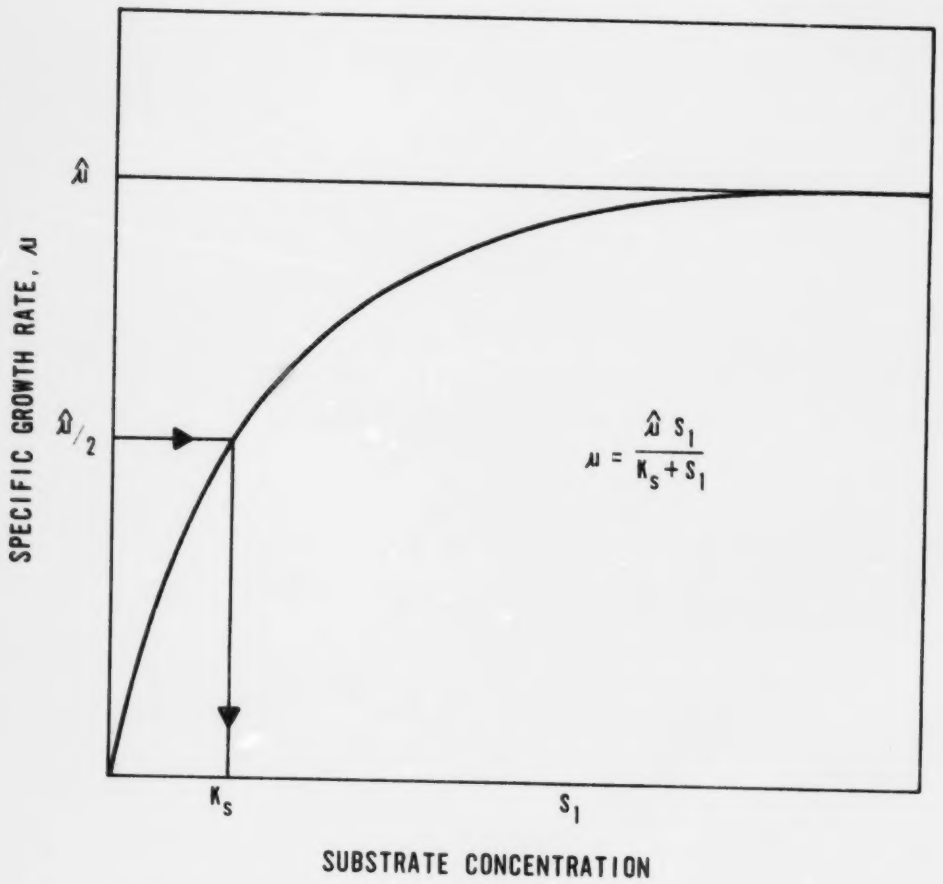


Figure 2 Michaelis–Menten (Monod) kinetic model

At steady state, $dX_1/dt = 0$, and

$$\frac{dX_1}{dt} = 0 = FX_0 - FX_2 - F_w(X_r - X_2) + (\mu - k_d)VX_1 \qquad (5)$$

or

$$\frac{1}{\theta_c} = \frac{F(X_2 - X_0) + F_w(X_r - X_2)}{X_1 V} = \mu - k_d \qquad (6)$$

where $F(X_2 - X_0) + F_w(X_r - X_2)$ = net growth of cells

$X_1 V$ = mass of cells in activated sludge system

θ_c = mean cell age.

In the absence of a practical method for estimating the biological activities of incoming cells, which are relatively insignificant compared to those in the reactor, the amount of active cells in the influent wastewater is assumed in the analysis to be negligible.

Similarly, a materials balance for cells around the reactor (see Figure 1) can be written as follows:

$$\begin{bmatrix}\text{rate of change of}\\ \text{cell biomass in}\\ \text{the reactor}\end{bmatrix} = \begin{bmatrix}\text{rate of}\\ \text{input of}\\ \text{cells}\end{bmatrix} - \begin{bmatrix}\text{rate of}\\ \text{output of}\\ \text{cells}\end{bmatrix} + \begin{bmatrix}\text{growth}\\ \text{rate of}\\ \text{cells}\end{bmatrix} - \begin{bmatrix}\text{decay}\\ \text{rate of}\\ \text{cells}\end{bmatrix}$$

or

$$V\frac{dX_1}{dt} = (FX_0 + F_r X_r - F_w X_r) - (F + F_r - F_w)X_1 + \mu X_1 V - k_d X_1 V \qquad (7)$$

Assuming that the process is at steady state, *i.e.*, $dX_1/dt = 0$, the following expression is obtained:

$$\frac{dX_1}{dt} = 0 = F(X_0 - X_1) + F_r(X_r - X_1) - F_w(X_r - X_1) + (\mu - k_d)VX_1$$

or $$\frac{1}{\theta_c} = \frac{F(X_1 - X_0) - F_r(X_r - X_1) + F_w(X_r - X_1)}{VX_1} = \mu - k_d \qquad (8)$$

It can be shown that Equations 6 and 8 are equivalent by applying a materials balance for biomass around the cell separator, *viz.*

$$FX_2 - F_wX_2 + F_rX_r = FX_1 + F_rX_1 - F_wX_1 \qquad (9)$$

or $$FX_2 - F_wX_2 = FX_1 - F_rX_r + F_rX_1 - F_wX_i \qquad (10)$$

Materials Balance for Substrate--

The materials balance for substrate around the system, which includes a reactor and cell separator with cell recycle, can be described as follows:

$$\begin{bmatrix}\text{rate of change}\\ \text{of substrate}\\ \text{in reactor}\end{bmatrix} = \begin{bmatrix}\text{rate of}\\ \text{input of}\\ \text{substrate}\end{bmatrix} - \begin{bmatrix}\text{rate of}\\ \text{output}\\ \text{of substrate}\end{bmatrix} - \begin{bmatrix}\text{rate of}\\ \text{uptake}\\ \text{of substrate}\end{bmatrix}$$

or $$V\frac{dS_1}{dt} = FS_0 - (F - F_w)S_1 - F_wS_1 - \text{uptake} \qquad (11)$$

The term "uptake" can be defined in terms of a yield coefficient, Y. Thus,

$$\text{uptake} = -\frac{dS}{dt}V = -\frac{dS}{dX}\frac{dX}{dt}V = \frac{\mu X}{Y}V \qquad (12)$$

Therefore, $$V\frac{dS_1}{dt} = F(S_0 - S_1) - \frac{\mu X_1 V}{Y} \qquad (13)$$

At steady state, $dS_1/dt = 0$, and

$$F(S_0 - S_1) = \frac{\mu X_1 V}{Y}$$

or $$X_1 = \frac{F(S_0 - S_1)Y}{V\mu} = \frac{(S_0 - S_1)Y}{\mu\theta} \qquad (14)$$

where θ = hydraulic residence time, V/F.

It should be noted that the specific growth rate is a function of the substrate removal velocity, q, which is a rational measure of the cellular removal activity, that is, the mass of substrate (BOD, COD, etc.) removed from the waste stream per unit mass of "active organism" per unit of time (g substrate removed)/(g cells)(day). Thus,

$$\mu = \frac{Y(S_0 - S_1)}{X_1\theta} = Yq \qquad (15)$$

where $$q = \frac{S_0 - S_1}{X_1\theta}$$

Substitution of Equation 15 into Equations 6 and 8 results in the cell continuity equation

$$\frac{1}{\theta_c} = \frac{F(X_2 - X_0) + F_w(X_r - X_2)}{VX_1} = \frac{Y(S_0 - S_1)}{X_1\theta} - k_d \qquad (16)$$

or $$\frac{1}{\theta_c} = \frac{F(X_1 - X_0) - (F_r - F_w)(X_r - X_1)}{VX_1} = \frac{Y(S_0 - S_1)}{X_1\theta} - k_d \qquad (17)$$

Solution of Equations 16 and 17 for the reactor substrate concentration, mean cell age, hydraulic residence time and cell concentration provides the following expressions:

$$\theta_c = \frac{VX_1}{F(X_2 - X_0) + F_w(X_r - X_2)} = \frac{VX_1}{F(X_1 - X_0) - (F_r - F_w)(X_r - X_1)} \qquad (18)$$

$$S_1 = \frac{YS_0 - (1/\theta_c + k_d)X_1\theta}{Y} \qquad (19)$$

$$X_1 = \frac{Y(S_0 - S_1)}{\theta(1/\theta_c + k_d)} \qquad (20)$$

and

$$\theta = \frac{Y(S_0 - S_1)}{X_1(1/\theta_c + k_d)} \tag{21}$$

The foregoing equations are of major significance indicating the interrelationships involved between the steady-state physical and biological parameters of the activated sludge system.

Process Efficiency

Process efficiency can be expressed as follows:

$$E = \frac{S_0 - S_1}{S_0} \tag{22}$$

Solution for $(S_0 - S_1)$ from Equations 3 and 15, and division of $(S_0 - S_1)$ by S_0, produces the following expression for efficiency:

$$E = \frac{\hat{\mu}\theta X_1 S_1}{S_0 Y(K_s + S_1)} \tag{23}$$

Thus the efficiency of an activated sludge process for a given influent substrate concentration is a function of hydraulic residence time, θ; cell concentration, X_1; yield coefficient, Y; maximum growth rate, $\hat{\mu}$; and half-saturation constant, K_s. It should be emphasized that once a given effluent concentration is specified, E is determined by the feed substrate concentration, S_0, and the hydraulic residence time, θ. The parameters $\hat{\mu}$, K_s and Y are kinetic constants and are determined by the microbiological characteristics of the system. Only the cell concentration, X_1, and the hydraulic residence time, θ, are variable in the system; however, only one of the two can be independently varied with time. Either X_1 or θ can be selected, but once a single parameter is fixed, the other automatically becomes fixed. From this, it can be concluded that either the efficiency, E, or the effluent concentration, S_1, should be correlated with the product of the reactor cell concentration, X_1, and hydraulic residence time, θ, (*viz.*, E or X_1 vs. $X_1\theta$).

Substrate and Nutrient Uptake and Removal

The biological species composition of activated sludge will vary widely and will depend on many factors, the most important of which are the nature of the organic substrate and the growth rate of the system. Thus it may be expected that the elemental composition of activated sludge will also vary widely.

Substrate and nutrient removals from wastewaters by activated sludge can be considered to be initially a high removal of suspended, colloidal and simple soluble substrate and nutrients followed by a slow progressive removal of complex soluble substrate and nutrients. Initial substrate and nutrient removal is accomplished by the following uptake mechanisms: (1) enmeshment of suspended matter in the biological flocs, (2) physico-chemical adsorption and absorption of colloidal matter on the biological flocs and (3) biosorption of soluble organic matter by the organisms. The colloidal and suspended materials must undergo breakdown to smaller molecules before they can become available for cellular synthesis.

Several mathematical models have been suggested to explain the mechanism of substrate and nutrient uptake by biological oxidation processes (References 9 and 10). These models have shown that at high substrate (or nutrient) levels the rate of substrate (or nutrient) uptake per unit of cells will remain constant (zero-order) to a limiting substrate (or nutrient) concentration below which the uptake rate will become concentration-dependent (first-order) and decrease.

At low substrate (or nutrient) concentration, the removal rate has a linear relationship with substrate (or nutrient) concentrations. The overall relationship between removal rate and concentration is believed to follow the Michaelis-Menten (Monod model) equation (see Figure 2), *viz.*,

$$q = \frac{\hat{q}\, S_1}{K_s + S_1} = \frac{\mu}{Y} \qquad (24)$$

where q = substrate (or nutrient) removal rate

$\hat{q}$ = maximum substrate (or nutrient) removal rate

Y = yield coefficient with respect to specific substrate (or nutrient).

The yield coefficient with respect to specific substrate or nutrient (nitrogen or phosphorus) generally is considered to be constant. By rearrangement of Equation 15, the yield coefficient can be related to substrate or nutrient uptake, $(S_0 - S_1)$; specific growth rate, μ; hydraulic residence time, θ; and steady-state cell concentration, X_1. Thus,

$$Y = \frac{\mu X_1 \theta}{S_0 - S_1} \tag{25}$$

Oxygen Requirements and Oxygen Transfer

Oxygen Requirements--

The activated sludge process is an aerobic process requiring a continuous supply of oxygen for the oxidation of substrate. In biological oxidation a portion of the energy released from substrate oxidation is stored by the attachment of a phosphate molecule to an adenosine diphosphate (ADP) molecule to form an adenosine triphosphate (ATP) molecule. The ATP molecule is later utilized in the performance of biological functions such as substrate transport across the cell wall and cell membrane against a concentration gradient, and biosynthesis.

Substrate entering a biological system is only partially oxidized as portions of the substrate are used in the synthesis of cell protoplasm. The degree of substrate oxidation is dependent on the bond energies and structure of the substrate. Although there are substantial differences in the degree of oxidation of a given substrate, an average relationship for estimating the oxygen requirement per unit mass of substrate can be developed.

Cell protoplasm and stored substrate, in addition to the influent substrate, are continuously being oxidized. This reduction of biomass

also requires oxygen and the total oxygen requirement for a given system is the sum of the oxygen requirement for decay or endogenous respiration and the oxygen requirement for substrate metabolism and subsequent biosynthesis.

Oxygen Transfer--

To estimate the quantity of oxygen transferred to the mixed liquor in activated sludge systems, it is convenient to identify the relationship between oxygen transfer and aerator power consumption. The consumption of oxygen per mass of substrate utilized and the oxygen requirement for sludge oxidation are primary considerations in the selection of aerators for activated sludge facilities and in the estimation of the operating costs of the activated sludge process.

Two principal theories--the penetration theory and the film theory--have been advanced to explain the transfer of oxygen (Reference 11). The penetration theory conforms to modern molecular kinetic theory which relates oxygen transport across a gas-liquid interface to the kinetic energy of the molecules and inter-molecular attractive forces. This approach appears to offer significant insights into the mechanics of oxygen transfer but has not been mathematically developed to the point where oxygen transfer in aeration basins can be modeled.

The film theory is based on a physical model in which two fictitious films--one liquid and one gas--exist at the gas-liquid interface. The gas molecules are transported to the outer face of the gas film by mixing and diffusion mechanisms. The gas molecules then diffuse across the stagnant gas film to the gas-liquid interface where they dissolve in the liquid film. The dissolved gas then diffuses through this stagnant film to the boundary between the film and the bulk liquid phase, from where it is transported throughout the bulk liquid phase by mixing. At the present time, the film theory is of greater practical value than the penetration theory, regardless of its questionable theoretical basis.

Process Kinetics with Oxygen Transfer--

Oxygen requirements can be expressed (Reference 12) as a linear function of the substrate removal velocity, q, and the endogenous respiration rate, k_d, as follows:

$$UV = a(\text{substrate removed}) + b(\text{cells oxidized}) = (O_2 \text{ used})/\text{day}$$

or
$$UV = aF(S_0 - S_1) + bk_dX_1V$$

or
$$U = \frac{a(S_0 - S_1)}{\theta} + \frac{bk_d(S_0 - S_1)}{q\theta} \qquad (26)$$

where U = rate of oxygen used

a = oxygen requirement per unit substrate removed

b = oxygen requirement per unit cell oxidized.

Thus,
$$U = \frac{S_0 - S_1}{\theta}(a + bk_d/q) \qquad (27)$$

The required oxygen transfer rate can be written as a function of hydraulic residence time, θ; effluent substrate concentration, S_1; and kinetic constants for the system, μ, Y, K_s, k_d, a and b. Thus,

$$U = \frac{Y(S_0 - S_1)(S_1 + K_s)}{\theta\hat{\mu}S_1}\left[\frac{a\hat{\mu}S_1}{Y(K_s + S_1)} + bk_d\right] \qquad (28)$$

With reasonable estimates of kinetic constants for a given waste treatment process, it is possible to estimate the oxygen transfer rate requirements for a wide range of influent, effluent and loading characteristics.

Active Organism Concentration

The most important single parameter in the activated sludge growth kinetic analysis is an accurate determination of active cell biomass. Various methods and parameters have been used to evaluate the active organism concentrations. Most microbiologists have used dry weight of suspended matter, volatile suspended solids, optical density, direct

cell count or viable cell count to evaluate cell concentration. Lawrence and McCarty (Reference 13) have used elementary cellular constituents, such as carbon, nitrogen and phosphorus, as active organism concentration parameters in anaerobic kinetic analysis. Agardy (Reference 14) used deoxyribonucleic acid (DNA) as an activity parameter in anaerobic digesters. Many workers have employed concentration of adenosine triphosphate (ATP) or dehydrogenase activity to express living cell concentration.

In the absence of a single accurate active organism concentration parameter to describe the activity of biological systems, several parameters were used in this demonstration study in addition to the traditional mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS). The additional parameter of dehydrogenase activity and adenosine triphosphate (ATP) were used to express biomass concentration for comparative purposes.

PROCESS PERFORMANCE PARAMETERS

The activated sludge process incorporates physical and biological processes which, for proper design and operation, requires a knowledge of several process variables and their interrelationships with process performance parameters. These independent performance parameters are organic loading velocity, L_V, and mean cell age, θ_c.

Organic Loading Velocity

One of the most important parameters of the activated sludge process is the organic loading velocity, or the food to organism ratio. The loading velocity, L_V, is equal to the mass of BOD applied per day per mass of VSS contained in the aeration tank, (mg BOD)/(mg VSS)(day). The values of loading velocities vary from a minimum of 0.05 (mg BOD)/(mg VSS)(day) for the extended aeration process to about 5 (mg BOD)/(mg VSS)(day) for the high-rate, supra-activation process (Reference 15).

Organic loading velocities have also been expressed in terms of mass of BOD applied per day per unit volume of aeration tank. Typical values range from 320 to 6,400 (kg BOD)/(1,000 m^3)(day) [20 to 400 (lb BOD)/(1,000 ft^3)(day)] for extended aeration and supra-activation processes, respectively. These volumetric loading velocity parameters neglect the cell concentration of mixed liquor and the food to organism ratio; however, they describe the minimum aeration tank volume that should be adequate for satisfactory treatment.

One of the principle objectives of this study was to define the effects of various loading velocities on the dependent variables. These dependent variables are effluent substrate concentration, sludge characteristics and nutrient removal efficiencies.

Mean Cell Age

Mean cell age, also termed mean cell or biological solids retention time, θ_c, is one of the operational parameters which have been proposed for the design and operational control of the activated sludge process. Mean cell age is a measure of the average residence time of the organisms in the system and can be expressed as follows:

$$\theta_c = \frac{VX_1}{F(X_2 - X_0) + F_w(X_r - X_2)} = \frac{VX_1}{F(X_1 - X_0) - (F_r - F_w)(X_r - X_1)} \qquad (18)$$

where $F(X_2 - X_0) + F_w(X_r - X_2)$ = loss of cells per day

VX_1 = cells in the system.

Values for mean cell ages range from three to four days for high-rate, 5 to 15 days for conventional and 20 to 30 days for extended aeration activated sludge processes.

It should be noted that the reciprocal of θ_c is the net growth rate, which is an important parameter for control of effluent quality as well as the entire activated sludge process.

Sludge Volume Index

Sludge settling and compaction characteristics are a primary requisite to successful operation of the activated sludge process. With a poor settling or bulking sludge, solids carry-over will contribute to the effluent BOD and suspended solids. Poor sludge compaction will result in a low concentration of return sludge solids, which in turn will limit the concentration of mixed liquor suspended solids in the aeration basin.

Sludge volume index, SVI, is defined as the volume in milliliters occupied per gram of activated sludge solids after a 1,000-ml mixed liquor sample has been allowed to settle in a graduated cylinder for 30 minutes. The return sludge concentration, X_r, can be expressed in terms of sludge volume index, SVI, as:

$$X_r = k \frac{10^6}{SVI} \tag{29}$$

where k = constant.

Similarly, the cell concentration in the mixed liquor, X_l, can be related to the settleability of sludge as follows:

$$X_l = \frac{F_r}{(F + F_r)} k \frac{10^6}{SVI} \tag{30}$$

It should be noted that when the sludge volume index is relatively high, i.e., greater than 100, it is difficult to maintain a high cell concentration in the mixed liquor even with a high return sludge ratio, $R_f = F_r/F$.

Organic loading velocity, L_v, appears to affect the sludge settleability and sludge volume index. At low loading velocities of less than 0.5 (mg BOD)/(mg VSS)(day), the sludge volume index has low values and sludge bulking is rarely encountered. As the loading velocity increases to about 0.5 (mg BOD)/(mg VSS)(day), the sludge volume index increases and an unstable settling condition is approached. Activated sludge systems loading velocities in the range of 0.5 to 2.0 (mg BOD)/(mg VSS)(day) could have sludge bulking problems.

SECTION VI

EXPERIMENTAL PROCEDURE AND ANALYTICAL METHOD

FACILITIES

Construction of the treatment facility for the City of Chino started in 1960. The initial facility consisted of one primary sedimentation tank, two oxidation ponds, one chlorination tank, one anaerobic digester, three sludge beds and a control building. The design capacity of the treatment facility was 0.044 m^3/sec (1 mgd).

To evaluate the potential of the optimum performance activated sludge system, construction of an activated sludge facility was completed in 1969 with the assistance of an EPA demonstration grant. The new facility includes two additional primary sedimentation tanks, three aeration basins, vibratory separation screens, two secondary clarifiers, chemical feeding equipment, a small-scale rapid sand filter bed, three small simulated recreational test ponds and a laboratory. The additional facilities constructed under this grant increased the design capacity of the plant to 0.13 m^3/sec (3 mgd).

The existing treatment facility and demonstration activated sludge facility are shown by a block-line diagram in Figure 3.

Barminution

Barminution is a unit operation for screening and reducing the size of larger particles to a predetermined size. The prc ess consists of trapping oversize particles on a bar screen and passing a rotating cutter periodically over the screen to reduce the size of the particles so that they will pass through the screen. The unit is a Chicago Pump Model "C"

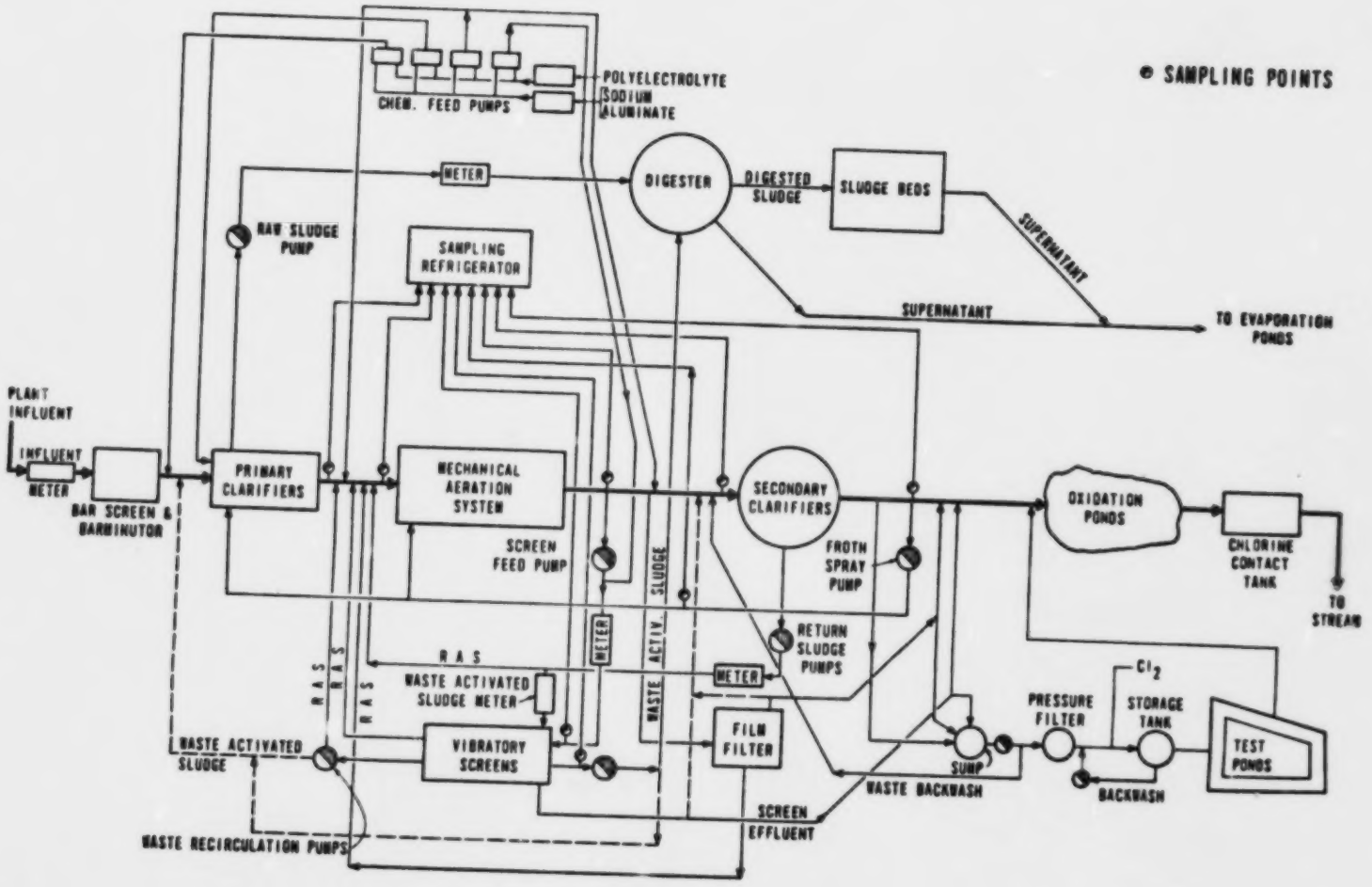


Figure 3 Water reclamation facilities of City of Chino

Barminutor for a 0.610-m (24-in.) channel and has a maximum continuous flow capacity of 0.285 m^3/sec (6.5 mgd). The unit is activated automatically when a predetermined headloss occurs across the screen. The bar screen opening in the barminutor is approximately 0.95 cm (0.375 in.). Provisions have been made in the barminution structure for influent bypassing through a coarse bar rack of the barminutor during maintenance periods.

Primary Clarifiers

Primary clarifiers have been installed to remove settleable solids for subsequent treatment by anaerobic digestion. The existing primary sedimentation tank and the two new clarifiers are 25.9 m (85 ft) long and 4.88 m (16 ft) wide with an average depth of 2.59 m (8.5 ft). The effluent weir system was designed for an overflow rate of 124 m^3/(day)(m) [10,000 gal/(day)(ft)].

The clarifiers are equipped with a flight system which draws settled sludge to the inlet end of the tank and which also skims the surface of the tank on their return. Sludge accumulates in a single hopper at the head-end of the tank where it is withdrawn periodically by means of a pumping system using two 1,090-m^3/day (200-gpm) WEMCO sludge pumps controlled by a sludge density meter. The skimmings are removed by hand-operated dipping skimmers to a sludge hopper equipped with a 1,090-m^3/day (200-gpm) WEMCO sludge pump.

Aeration Tanks

Three aeration tanks of varying size provided flexibility in operation. Aeration tank volumes are 240, 708 and 477 m^3 (63,300, 187,000 and 126,000 gal), which in various combinations at a flow of 0.13 m^3/sec (3 mgd) provided hydraulic retention times ranging from 0.5 to 3.0 hr. The primary effluent can be fed to any or all tanks through meter gates. Return activated sludge can be introduced directly to the first tank or can be added to the effluent from the primary clarifiers.

Aeration Equipment

Careful consideration was given to the selection of aeration equipment for the proposed accelerated high-rate activated sludge system. The new deep-cone EIMCO-SIMCAR mechanical aerators with dissolved oxygen concentration control were employed. The dissolved oxygen concentration was sensed with a Honeywell dissolved oxygen probe and was controlled through an automated weir that varies the submergence of the aerators in order to maintain a preset dissolved oxygen concentration.

Three mechanical aerators were used, having maximum electrical energy requirements of 11, 19 and 56 kw (15, 25 and 75 hp), respectively; and in addition, an extra impeller designed for a 45-kw (60-hp) driver was purchased. Each aerator is designed so it provides approximately ten inches of impeller submergence.

Anti-vortex baffles were installed in each aeration tank. The baffles consist of two large crossed plates mounted on the bottom of the basin beneath the aerator.

Solids Separation Facilities

Four solids separation devices--plain sedimentation secondary clarifiers, vibratory screens, pressure filters and dissolved air flotators--were employed for the separation of activated sludge during the study period.

Secondary Clarifiers--

Two circular clarifiers are provided with sludge drawoff by suction from three zones on each arm of the clarifier. These units are equipped with provisions for adjusting the flow of each pickup zone. Each of the two clarifiers is 16.8 m (55 ft) in diameter and has an average water depth of 2.7 m (9 ft). At an influent flow rate of 0.13 m^3/sec (3 mgd), the overflow rate is 25.6 $m^3/(m^2)(day)$ [630 $gal/(ft^2)(day)$] with a weir rate of 110 $m^3/(day)(m)$ [8,900 gal/(day)(ft)]. These units are equipped with a central feed well approximately 2.90 m (9.5 ft) in diameter.

Vibratory Screen Facility--

The SWECO vibratory screen separator was tested as a method for rapidly separating and concentrating a substantial portion of the activated sludge and was followed by secondary clarifiers to capture the fines passing through the screens. The purposes for the vibratory screens were (1) to reduce the detention time for separating the mixed liquor, thus reducing the potential for anaerobic conditions and thereby reducing the possible release of sorbed or incorporated nutrients from the activated sludge cells to the effluent; (2) to provide a means for separating filamentous sludges should they develop under the high loading rate conditions; and (3) to provide a mixed liquor separating system that would be compatible with the goal of reducing the plant size. A two-week trial run on separating mixed liquor in a nearby conventional activated sludge treatment facility suggested that overflow rates with vibratory screens could be two to three times the level of conventional gravity secondary settling. Each screen unit was equipped with a spray system consisting of nozzles mounted in a piping configuration similar to the spokes of a wheel. The system was automated so that the sprayers would activate for a short interval at an adjustable frequency. Each screen was fed from a common trough. The flowrate of the feed was controlled by an adjustable V-notch weir.

Eight SWECO vibratory screens were installed. Six of the units were mounted on two supporting beams and two units were mounted over hoppers leading to two sludge pumps. One pump was set up to pump the sludge to the digester and the other to return the sludge to the aeration tanks.

Two of the eight screens were stacked in series configuration so that the screening could be done in stages. These two units were equipped with 0.044-mm opening (325-mesh) screens, followed in one case by a 0.029-mm opening (500-mesh) nylon screen and in the other case by a 0.014- by 0.105-mm opening (720- by 140-mesh) dutch twill stainless steel screen. The remaining six screen units were equipped as follows: two with a 0.044-mm opening (325-mesh) stainless steel screens, two with 0.037-mm opening (400-mesh) stainless steel screens, one with 0.029-mm

opening (500-mesh) nylon screens and one with 0.014- by 0.105-mm opening (700- by 140-mesh) dutch twill stainless steel screens.

Pressure Filtration Unit--

A small rapid sand filtration facility was constructed to polish secondary effluent before discharging into three small ponds. The unit consisted of a 0.914-m (36-in.) diameter INFILCO standard rapid sand filter. The facility is equipped with a feed pump, a backwash storage tank and pump, a chemical feed pump and a batch tank.

Dissolved Air Flotation Unit--

An EIMCO pilot dissolved air flotation plant was leased in an effort to thoroughly investigate alternative solids separation systems. The pilot unit was approximately 1.52 m (5 ft) in diameter and was equipped with a complete float skimming system, bottoms rakes and a drawoff for settled solids. The unit was also equipped with EIMCO's two-stage pressurization system for dissolving air in a recycle stream drawn from the effluent of the unit.

Chlorination Facilities

Existing chlorination facilities were enlarged by the addition of another W & T A-731 V-notch 400-16 Chlorinator. The existing 108-m^3 (28,600-gal) chlorine contact tank was retained, which provides retention time of 13.8 minutes at a flow rate of 0.13 m^3/sec (3 mgd).

Chemical Feed Facilities

A chemical feed system was installed as a backup to aid in the overall wastewater treatment, particularly if polymer aids were needed for mixed liquor separation or chemical treatment was needed for phosphate removal. The overall Prado Dam (Chino area) plans called for using the plant effluent for recreational purposes. The chemical feed facilities were designed so that polymer aids and/or chemicals could be added at any point in the treatment facility (from raw wastewater to secondary effluent). Due to time constraints, the chemical feed system was not used extensively during the 15-month study.

The chemical feed facilities included a 1.08-m^3 (285-gal) storage tank, a 0.12-m^3 (33-gal) reserve tank and a variable-speed positive-displacement pump which could be paced to the plant influent flowrate. The chemical feed facilities also included a variable-speed pumping unit and a lined 15.1-m^3 (4,000-gal) liquid chemical storage tank.

Recreational Eutrophication Ponds

Three existing oxidation ponds of 3,750-, 3,750- and 23,400-m^3 [3.04-, 3.04- and 19.0-(acre)(ft)] capacity, respectively, and 1.1-m (3.5-ft) deep were augmented with three simulated recreational ponds. The simulated recreational ponds are 1.1-m (3.5-ft) deep and possess a capacity of approximately 740 m^3 [0.6(acre)(ft)] each. The purpose for the recreational ponds was to study the suitability of using the plant effluent for recreational purposes.

OPERATION PROCEDURE

The operation procedure for the optimum activated sludge system consisted of two phases—accelerated activated sludge operation and testing of alternative solids separation systems during the 15-month study.

The raw sewage from the City of Chino entered the rectangular primary clarifiers through a barminutor. Settleable solids, removed in the primary clarifiers, were pumped to an anaerobic digester, while clarified wastewater was pumped continuously to the aeration tanks. Constant hydraulic flowrate was achieved by utilizing one aeration tank as a primary effluent equalizing basin from which the primary effluent could be pumped at a constant flowrate to the aeration system. Mixed liquor from the aeration tanks was introduced to alternative solids separation systems, from where return activated sludge was pumped continuously to the aeration tanks. Sludge wasting was accomplished by pumping directly from the return activated sludge lines. Digester supernatant was not recycled to the plant but was discharged directly to the oxidation ponds.

Steady-State Operation

Steady-state activated sludge operation is desirable for characterizing biological oxidation kinetics. Theoretically, the substrate and

nutrient input concentrations, the active biomass concentration, the hydraulic residence time, the return activated sludge flowrate, the dissolved oxygen concentration and temperature should be controlled at constant levels for complete biological kinetic analysis.

By directly controlling the hydraulic residence time, the activated sludge concentration and the dissolved oxygen concentration in the mixed liquor, a series of presumed steady-state operations were completed during the study period. Steady-state for the purposes of this study was defined as a period wherein the hydraulic residence time, the substrate concentration in the primary effluent and the biomass concentration in the mixed liquor, determined at daily intervals, did not vary more than ±20 percent from a mean value. The variation of each parameter was required to be random, *i.e.*, each parameter could not exhibit a consistent upward or downward trend.

Sampling and Metering

The sampling system designed for Chino contains five basic elements: a controller, a positive-displacement pump, a three-way solenoid valve, a triggering clock and a refrigerator. When in operation the controller receives a signal from a selected flowmeter and paces the withdrawal rate of the sampling pump to the flowrate. The pump delivers a continuous stream to a three-way solenoid valve which is open to waste. The triggering clock diverts the stream to the refrigerated sample bottle for a short fixed interval at an adjustable frequency. This automatic sampling system was installed to sample the primary effluent, mixed liquor, secondary effluent and the return activated sludge from the secondary clarifiers.

All metering in the facility was performed by Venturi metering systems with a continuous backflow of wash water through the meter. Raw sewage input flowrates, flowrates of primary effluent to the aeration tanks, return activated sludge flowrates, waste sludge flowrates and primary sludge pumping flowrates were metered and recorded. Table 1 presents the location of sampling and metering stations at the plant.

Table 1. PROCESS MONITORING CHARACTERISTICS AND DAILY ROUTINE LABORATORY ANALYSES

Process Location	Flowmeter	Sampling	Analyses
Primary effluent	Venturi flowmeter Automatic recording	Automatic sampling and refrigeration	Suspended solids (SS) Volatile suspended solids (VSS) Biochemical oxygen demand (BOD) Chemical oxygen demand (COD) Total and dissolved Kjeldahl nitrogen Total and dissolved total phosphate
		Grab sampling	Dissolved NO_2^-, NO_3^- and $PO_4^{\equiv}$
Mixed liquor	--	Automatic sampling and refrigeration	Mixed liquor volatile suspended solids (MLVSS) Mixed liquor suspended solids (MLSS) Temperature Sludge volume index (SVI) Total and dissolved Kjeldahl nitrogen Total and dissolved total phosphate Biochemical oxygen demand (BOD) Chemical oxygen demand (COD)
		Grab sampling	Dissolved NO_2^-, NO_3^-, and $PO_4^{\equiv}$
Secondary effluent	--	Automatic sampling and refrigeration	Suspended solids (SS) Volatile suspended solids (VSS) Turbidity Biochemical oxygen demand (BOD) Chemical oxygen demand (COD) Total and dissolved Kjeldahl nitrogen Total and dissolved total phosphate
		Grab sampling	Dissolved NO_2^-, NO_3^- and $PO_4^{\equiv}$
Return activated sludge	Venturi flowmeter Automatic recording	Automatic sampling and refrigeration	Suspended solids (SS)
Waste activated sludge	Venturi flowmeter Automatic recording	Automatic sampling and refrigeration	Suspended solids (SS)

ANALYTICAL METHODS

A summary tabulation of the daily, routine laboratory tests performed on the various process stream samples is presented in Table 1.

Wherever possible, *Standard Methods for the Examination of Water and Wastewater*, 13th edition (Reference 16) was followed for substrate, nutrient and biomass measurements. Details of nonstandard analytical methods are presented in Appendix A.

Substrate Analyses

Chemical Oxygen Demand (COD)--

Chemical oxygen demand was determined by dichromate reflux method according to *Standard Methods for the Examination of Water and Wastewater* (Reference 16).

Biochemical Oxygen Demand (BOD)--

The five-day biochemical oxygen demand determination was made according to the procedure outlined in *Standard Methods for the Examination of Water and Wastewater* (Reference 16). Dissolved oxygen measurements were made using a polarographic dissolved oxygen probe.

Nutrient Analyses

Total Kjeldahl Nitrogen--

Total Kjeldahl nitrogen was determined using the procedure outlined in *FWPCA Methods for Chemical Analysis of Water and Wastes* (Reference 17). Distillation was carried out at a pH of 9.5 and the ammonia content of the distillate was measured titrimetrically.

Nitrate Nitrogen--

Nitrate nitrogen was determined using the procedure outlined in *Standard Methods for the Examination of Water and Wastewater* (Reference 16). Color produced by the reaction between nitrate and phenoldisulfonic acid was measured with a Bausch and Lomb Spectronic 20 at a wavelength of 410 mμ.

Nitrite Nitrogen--

Nitrite nitrogen was determined according to analytical methods outlined in *FWPCA Methods for Chemical Analysis of Water and Wastes* (Reference 17). The color developed by diazotization of the water with sulphanilamide and then coupling with N-(1-naphthyl)ethylenediamine was measured using a Bausch and Lomb Spectronic 20 at a wavelength of 540 mμ.

Orthophosphate--

Orthophosphate was determined using the stannous chloride method listed in *Standard Methods for the Examination of Water and Wastewater* (Reference 16). Molybdophosphoric acid is reduced to the intensely colored complex, molybdenum blue, by stannous chloride. The color was measured photometrically at a wavelength of 690 mμ.

Total Phosphate--

Total phosphate was determined using the persulfate digestion method followed by stannous chloride orthophosphate determination as outlined in *Standard Methods for the Examination of Water and Wastewater* (Reference 16).

Biomass Analyses

Volatile Suspended Solids--

Volatile suspended solids concentration was determined according to the filtration procedure outlined in *Standard Methods for the Examination of Water and Wastewater* (Reference 16).

Adenosine Triphosphate (ATP)--

The adenosine triphosphate (ATP) measurement procedure was developed from the work of Patterson, Brezonik and Putnam (Reference 18) and Beutler and Baluda (Reference 19). The amount of light produced by firefly extract is directly proportional to the amount of ATP added. Detailed procedures of the analytical method used are presented in Appendix A.

Dehydrogenase Activity--

Triphenyl tetraxolium chloride (TTC) is reduced by dehydrogenase to triphenyl formazan (TF). Dehydrogenase activity can be measured spectrophotometrically because the color produced by triphenyl formazan is proportional to the dehydrogenase activity. The details of the analytical procedure used are included in Appendix A.

Sludge Volume Index

Sludge settling tests were conducted in a 1,000-ml cylinder. The sludge volume index, SVI, was computed by dividing the 30-minute sludge volume (ml) by the initial suspended solids concentration (g/l).

DATA PROCESSING AND COMPUTATIONAL METHODS

Data Processing

Two of the key parameters in the kinetic description of the activated sludge process are the substrate removal velocity, q, and the net system growth rate, $1/\theta_c$, or mean cell age, θ_c. Net system growth rate and substrate removal velocity were calculated using the following equatations:

$$q = \frac{S_0 - S_1}{X_1 \theta} \tag{15}$$

and

$$1/\theta_c = \frac{F(X_2 - X_0) + F_w(X_r - X_2)}{VX_1} \tag{16}$$

The active biological solids measure, X_1, was expressed as the volatile suspended solids in the mixed liquor (MLVSS), the ATP content of the mixed liquor or the dehydrogenase activity of activated sludge. It should be noted that the substrate removal relationship can also be used to describe nutrient (N and P) removal velocities. The influent substrate (or nutrient) concentration, S_0, was determined by total BOD or COD (or various N and P species) in primary effluent; and effluent substrate (or nutrient) concentration, S_1, was determined as soluble effluent BOD or COD (or various N and P species) in final effluent.

Daily calculations of net growth rates and hydraulic residence times and daily determination of mixed liquor volatile suspended solids concentrations were used to establish periods of steady-state operation. Steady-state conditions were defined as periods in which the net growth rate, hydraulic residence time or MLVSS did not vary more than ±20 percent. Data obtained during these steady-state periods were used in subsequent calculations and kinetic evaluations.

Computational Methods

A computer linear least-square regression analysis was used to estimate the kinetic constants from the linear cell continuity equation, $1/\theta_c = Yq - k_d$, and all linear transformations from the Michaelis-Menten (Monod) equation, $q = \frac{\hat{q}\, S_1}{K_s + S_1}$. The linear transformations are:

(1) $$\frac{1}{q} = \frac{K_s}{\hat{q}} \left(\frac{1}{S_1}\right) + \frac{1}{\hat{q}} \qquad (31)$$

(2) $$S_1 = \left(\frac{S_1}{q}\right) \hat{q} - K_s \qquad (32)$$

(3) $$q = \hat{q} - K_s \left(\frac{q}{S_1}\right) \qquad (33)$$

A nonlinear computer program (Reference 20) was also used to estimate the kinetic constants directly from nonlinear regression analyses.

SECTION VII

RESULTS AND DISCUSSION

WASTE CHARACTERIZATION

The City of Chino is a community with a sewered population of approximately 16,000 residents plus an additional 2,000 prisoners of the State of California, and is served by the Chino Water Reclamation Facilities. The only industrial operation served by the sewer system is a small meat packing plant, which has a pretreatment system consisting of a small sedimentation tank, a storage tank for impounding blood prior to removal via trucks and a separate manure handling facility. In general, the wastewater at Chino is similar to typical domestic waste as the industrial contribution is small and partially pretreated.

No attempt was made to characterize the organic pollutant concentration in the raw waste reaching the treatment plant; all characterizations presented herein, except raw waste flow, were made on primary effluent. Table 2 presents daily waste characterizations measured during the steady-state periods. Waste characteristics monitored include raw waste flow, total BOD and COD, soluble BOD, total and volatile suspended solids, and various nitrogen and phosphorus species in the primary effluent. Average values are summarized in Table 3.

The raw waste flow at Chino ranged from 0.0890 to 0.122 m^3/sec (1.85 to 2.79 mgd), with an average flow of 0.0972 m^3/sec (2.22 mgd). Approximately one-tenth of this flow was contributed by the prison complex. The contribution from the meat packing plant was estimated to be also one-tenth of the total flow.

Table 2. PRIMARY EFFLUENT WASTEWATER CHARACTERIZATION

Date	Raw sewage flow, m^3/sec	Primary effluent				
		Total BOD, mg/l	Soluble BOD, mg/l	Total COD, mg/l	Total suspended solids, mg/l	Volatile suspended solids, mg/l
16 Dec 70	--	126	--	202	130	130
17	--	162	--	260	78	55
18	--	210	--	238	68	63
19	--	84	--	252	135	90
20	--	132	--	245	110	104
21	--	168	--	264	125	115
31	--	150	--	319	105	100
2 Jan 71	--	108	--	379	105	98
3	--	102	--	313	143	133
5	--	132	--	432	123	95
15 Jan 71	--	168	--	500	210	167
16	--	162	--	396	140	120
17	--	156	--	239	223	130
18	--	198	--	245	220	220
15 Apr 71	0.102	126	--	375	117	113
16	0.119	114	--	365	83	72
18	0.0924	84	--	296	78	55
19	0.0964	72	--	349	107	80
09 May 71	--	108	--	262	73	64
11	0.0977	108	--	323	131	131

Table 2 (continued). PRIMARY EFFLUENT WASTEWATER CHARACTERIZATION

Date	Raw sewage flow, m^3/sec	Primary effluent				
		Total BOD, mg/l	Soluble BOD, mg/l	Total COD, mg/l	Total suspended solids, mg/l	Volatile suspended solids, mg/l
12 May 71	0.0920	168	--	402	160	160
13	0.0929	144	--	510	215	215
14	0.0920	108	--	415	160	160
16	0.0920	84	--	308	95	95
17	0.0872	96	--	318	97	97
18	0.0964	96	--	364	110	110
19 May 71	0.0933	90	--	357	128	98
20	0.0955	108	--	390	130	65
21	0.0937	138	--	584	223	195
23	0.0924	162	--	460	233	185
24	0.0889	160	--	423	173	158
25	0.0981	156	--	389	155	113
28	0.0933	98	--	560	131	110
29	0.0911	108	--	364	120	105
16 Aug 71	0.0823	120	60	342	122	90
17	0.0924	94	--	290	148	127
20	0.0867	108	59	279	120	80
23	0.0810	150	57	341	125	93
24	0.0929	126	45	265	107	70
25	0.0907	138	57	301	130	88
26	0.0907	153	63	292	110	75

Table 2 (continued). PRIMARY EFFLUENT WASTEWATER CHARACTERIZATION

Date	Raw sewage flow, m^3/sec	Primary effluent				
		Total BOD, mg/l	Soluble BOD, mg/l	Total COD, mg/l	Total suspended solids, mg/l	Volatile suspended solids, mg/l
28 Aug 71	0.0915	132	48	322	122	75
29	0.0915	102	60	258	73	63
30	0.0841	108	36	277	108	82
31	0.0968	120	66	454	212	155
5 Sep 71	0.0915	150	60	306	110	87
6	0.0823	132	66	293	97	79
9	0.0972	108	54	281	80	67
11	0.0964	72	36	279	69	59
12	0.0937	120	60	328	88	69
13	0.0933	90	48	308	70	57
14	0.0102	135	57	313	107	48
16	0.100	132	71	314	112	84
17	0.100	138	48	267	95	80
19	0.0990	102	31	278	116	88
20	0.0955	108	54	313	116	88
28 Sep 71	0.100	153	78	337	108	79
29	0.0959	120	56	358	108	84
10 Oct 71	0.113	156	23	582	290	240
3	0.110	120	57	307	76	49
4	0.105	78	42	319	75	63
5	0.115	114	59	304	109	71
6	0.0972	105	36	339	117	81

Table 2 (continued). PRIMARY EFFLUENT WASTEWATER CHARACTERIZATION

Date	Raw sewage flow, m^3/sec	Primary effluent				
		Total BOD, mg/l	Soluble BOD, mg/l	Total COD, mg/l	Total suspended solids, mg/l	Volatile suspended solids, mg/l
7 Oct 71	0.104	96	53	380	78	65
9	0.0986	87	59	333	72	72
10	0.0977	108	63	347	109	109
11	0.0942	144	81	395	137	137
9 Nov 71	0.0999	113	66	408	112	88
10	0.100	116	72	382	120	106
14	0.0950	88	42	317	74	59
23	0.0994	96	64	321	103	61
24	0.0981	79	44	303	108	60
25	0.0972	111	72	332	147	96
26	0.0920	114	50	328	115	81
29		79	47	276	57	29
1 Jan 72	0.111	160	71	491	238	205
2	0.122	152	68	365	113	104
5	0.116	105	70	353	159	99
6	0.104	156	80	393	162	104
8	0.101	84	43	363	185	76
10	0.100	128	65	363	110	94
12	0.102	113	68	404	112	92

Table 3. SUMMARY OF PRIMARY EFFLUENT WASTEWATER CHARACTERIZATION

Characteristic	Unit	Range	Average
Raw Waste Flow	m^3/sec	0.0890 - 0.122	0.0972
Primary effluents			
Substrate			
Total BOD[a]	mg/l	72 - 210	122
Soluble BOD[a]	mg/l	23 - 80	56.9
Total COD[a]	mg/l	202 - 584	345
Suspended solids			
TSS[a]	mg/l	57 - 290	125
VSS[a]	mg/l	29 - 240	100
Nitrogen			
Total Kjeldahl nitrogen[a]	mg/l as N	24.8 - 61.1	38.8
Dissolved Kjeldahl nitrogen[a]	mg/l as N	24.1 - 47.8	33.5
Total ammonia nitrogen[b]	mg/l as N	18.1 - 32.2	23.0
Dissolved nitrite and nitrate nitrogen[b]	mg/l as N	0.00 - 0.64	0.08
Total dissolved nitrogen[c]	mg/l as N	24.1 - 47.8	33.6
Total nitrogen[d]	mg/l as N	24.8 - 61.1	38.9
Phosphorus			
Dissolved orthophosphate[b]	mg/l as P	7.4 - 17.0	11.3
Total dissolved phosphate[a]	mg/l as P	6.6 - 25.2	14.8
Total phosphate[a]	mg/l as P	7.1 - 27.5	17.8

[a]Daily grab sample.

[b]Three-day composite sample.

[c]Sum of dissolved Kjeldahl nitrogen and dissolved nitrite and nitrate nitrogen.

[d]Sum of total Kjeldahl nitrogen and dissolved nitrite and nitrate nitrogen.

Total BOD in the primary effluent varied from 72 to 210 mg/l with an average of 122 mg/l, of which 56.9 mg/l or 46.7 percent was soluble.

Total COD ranged from 202 to 584 mg/l, with an average of 345 mg/l. Assuming that 30 percent of the total BOD and COD is removed by primary sedimentation, this corresponds to a raw wastewater strength of 174 mg/l of BOD and 494 mg/l of COD. Total suspended solids in the primary effluent varied from 57 to 290 mg/l, with an average of 125 mg/l, of which 100 mg/l or 80 percent was volatile.

Average values of various nitrogen and phosphorus species concentrations are presented in Table 3.

KINETIC CHARACTERIZATION OF ACCELERATED HIGH-RATE ACTIVATED SLUDGE SYSTEM

By direct control of the hydraulic residence time and the return sludge rate and, thereby, the mixed liquor volatile suspended solids, a series of nine periods of steady-state operation were conducted during the study. Table 4 summarizes the mean values of steady-state performance parameters of hydraulic residence time, mean cell age, mixed liquor sludge concentration (MLVSS), substrate loading velocities, temperature and the number of steady-state measurements for each period.

The activated sludge system was operated at hydraulic residence times of from 0.97 to 5.16 hours. The mean cell age of activated sludge in the system was varied from 0.446 to 32.4 days. This wide range of mean cell ages indicates that the system was operated from a very low-rate system (net growth rate = 0.0363 day^{-1}) to a high-rate system (net growth rate = 2.16 day^{-1}). Substrate loading velocities ranged from 0.245 to 2.61 (mg BOD)/(mg MLVSS)(day) and 0.542 to 8.53 (mg COD)/(mg MLVSS)(day). The corresponding substrate removal velocities ranged from 0.229 to 2.33 (mg BOD removed)/(mg MLVSS)(day) and 0.365 to 6.57 (mg COD removed)/(mg MLVSS)(day). These substrate loading and removal velocities correspond to process substrate removal efficiencies of 88 percent BOD removal and 75 percent COD removal, which exceeded the goal of 80 percent BOD removal for the demonstration.

Table 4. MEAN VALUES OF STEADY-STATE PERFORMANCE PARAMETERS

Steady-state run	Number of steady-state measurements	Temperature, °C	Aeration volume, m^3	Hydraulic residence time, day	Mean cell age, day	Net growth rate, day^{-1}	MLVSS, mg/l	BOD loading velocity, (mgBOD)/(mgVSS)(day)	COD loading velocity, (mgCOD)/(mgVSS)(day)
1[a]	10	18	939	0.215	32.4	0.0363	2520	0.261	0.542
2[a]	4	18	939	0.173	16.6	0.0709	3220	0.307	0.622
3	4	19	240	0.108	3.17	0.317	3690	0.245	0.872
4	8	20	240	0.0754	1.58	0.650	2300	0.659	2.09
5	8	20	240	0.0725	1.39	0.726	2550	0.683	2.39
6	22	25	240	0.0403	0.737	1.34	1760	1.70	4.33
7	11	23	240	0.0412	0.525	1.94	1050	2.61	8.53
8	8	20	240	0.0410	1.57	0.643	2410	1.03	3.45
9	7	18	240	0.0442	0.0442	2.16	1120	2.61	8.05

[a]System operated at low rate.

As discussed previously, conventional activated sludge systems operate at organic loading velocities ranging from 0.2 to 0.5 (mg BOD)/(mg MLVSS) (day), with mean cell ages varying from five to 15 days and MLVSS's ranging from 1,500 to 3,000 mg/l. On the other hand, high-rate systems operate at substrate loading rates of 0.4 to 2.0 (mg BOD)/(mg MLVSS)(day), with mean cell ages of three to four days and MLVSS's of from 500 to 1,500 mg/l. Comparing these operational parameters with the performance parameters reported in Table 4, it is apparent that the system in this study was operated from a very low-rate system (Steady-State Period 1), through a conventional activated sludge system (Steady-State Period 2), to a high-rate system (Steady-State Periods 3 through 9).

Temperature of the mixed liquor varied on the average from 17 to 26°C during the steady-state runs. Although biological, hence activated sludge, growth rate is a function of temperature, the effect of temperature on system kinetic characteristics could not be evaluated in this study due to limited and incomplete information on activated sludge system performance under various temperatures and system growth rates.

The daily measurements conducted during the presumed steady-state periods are presented in Table 5, which includes the steady-state MLVSS concentration, primary effluent substrate concentration (total BOD and COD), primary effluent total and volatile suspended solids concentration, secondary effluent substrate concentration (total and soluble BOD and COD), cell concentration (VSS), aeration tank volume, input rate of primary effluent, return activated sludge flowrate and waste activated sludge flowrate.

Pertinent process characteristics and performance parameters are summarized in Table 6. These daily performance characteristics are hydraulic residence time, mean cell age, substrate (BOD and COD) removal and loading velocities and process efficiency (BOD and COD removals). In calculating the process characteristics and performance parameters, it was assumed that both soluble and particulate BOD or COD in the primary effluent are available substrate for cellular growth. Because most particulates in secondary effluent are biological cells and effluent solids

Table 5. SUMMARY OF STEADY-STATE MEASUREMENTS

Date	Steady-state period	Primary effluent VSS, mg/l	MLVSS, mg/l	Secondary effluent TSS, mg/l	Secondary effluent VSS, mg/l	Return sludge VSS, mg/l	Primary effluent total COD, mg/l	Primary effluent total BOD, mg/l
16Dec70	1	130	1900	24	11	4090	202	126
17Dec70	1	55	2270	18	15	2270	260	162
18Dec70	1	63	2360	13	8	5110	238	210
19Dec70	1	90	2850	31	15	2960	252	84
20Dec70	1	104	2980	25	25	1050	245	132
21Dec70	1	115	2860	15	15	4210	264	168
31Dec70	1	100	2010	32	30	4260	319	150
2Jan71	1	98	2530	24	22	6300	379	108
3Jan71	1	133	2370	31	24	4070	313	102
5Jan71	1	95	3060	32	29	6300	432	132
15Jan71	2	167	3420	70	48	6810	500	168
16Jan71	2	120	2960	42	36	8170	396	162
17Jan71	2	130	3070	18	18	9090	239	156
18Jan71	2	220	3410	58	58	8680	245	198
15Apr71	3	113	4290	35	35	7370	375	126
16Apr71	3	72	3480	33	31	7000	365	114
18Apr71	3	55	3610	23	22	7150	296	84
19Apr71	3	80	3360	32	27	6380	349	72
9May71	4	64	2270	16	14	6090	262	108
11May71	4	131	2160	55	12	5750	323	108
12May71	4	160	2180	35	27	5880	402	168
13May71	4	215	2540	2	2	5530	510	144
14May71	4	160	2220	32	26	5530	415	108
16May71	4	95	2410	22	16	6760	308	84
17May71	4	97	2420	21	21	6890	318	96
18May71	4	110	2230	28	18	4300	364	96

Date	Secondary effluent total COD, mg/l	Secondary effluent soluble COD, mg/l	Secondary effluent total BOD, mg/l	Secondary effluent soluble BOD, mg/l	Primary effluent flowrate, m^3/hr	Return sludge flowrate, m^3/hr	Waste sludge flowrate, m^3/hr	Aeration tank volume, m^3
16Dec70	100	60	10	11	182	129	0.00	939
17Dec70	99	99	41	26	182	135	0.00	939
18Dec70	92	119	61	24	182	145	0.00	939
19Dec70	81	99	14	20	182	144	0.00	939
20Dec70	75	80	18	19	182	140	0.00	939
21Dec70	76	85	21	19	182	146	0.00	939
31Dec70	106	160	14	15	182	134	0.02	939
2Jan71	84	74	7	14	182	129	0.00	939
3Jan71	94	83	13	14	182	134	0.00	939
5Jan71	84	63	17	11	182	124	0.00	939
15Jan71	298	181	19	19	227	119	0.00	939
16Jan71	156	115	23	11	227	149	0.00	939
17Jan71	130	76	26	13	225	141	0.00	939
18Jan71	128	85	7	12	225	113	0.00	939
15Apr71	115	83	18	8	91	62	1.5	240
16Apr71	115	89	19	8	85	66	1.0	240
18Apr71	101	75	14	7	96	69	1.4	240
19Apr71	103	77	14	10	96	62	1.4	240
9May71	67	62	12	6	136	79	2.3	240
11May71	87	77	20	10	131	76	2.2	240
12May71	88	62	23	11	131	76	2.2	240
13May71	88	82	10	7	134	76	2.1	240
14May71	104	93	17	11	131	72	2.1	240
16May71	77	72	8	6	131	71	2.2	240
17May71	77	67	12	10	136	72	2.2	240
18May71	77	72	10	10	131	62	2.2	240

Table 5 (continued). SUMMARY OF STEADY-STATE MEASUREMENTS

Date	Steady-state period	Primary effluent VSS, mg/l	MLVSS, mg/l	Secondary effluent TSS, mg/l	Secondary effluent VSS, mg/l	Return sludge VSS, mg/l	Primary effluent total COD, mg/l	Primary effluent total BOD, mg/l
19May71	5	98	2550	26	23	7270	357	90
20May71	5	65	2430	42	32	6270	390	108
21May71	5	195	2560	25	24	6300	584	138
24May71	5	185	2750	20	19	6970	460	162
25May71	5	158	2830	25	25	6990	423	160
28May71	5	113	2450	22	17	6610	389	156
29May71	5	110	2520	44	34	5990	560	96
		105	2320	38	34	5850	364	108
16Aug71	6	90	1920	43	46	3760	342	120
17Aug71	6	127	2190	56	49	4330	290	94
20Aug71	6	80	1800	45	40	4590	279	108
23Aug71	6	93	1810	28	31	5690	341	150
24Aug71	6	70	1540	32	25	4180	265	126
25Aug71	6	88	1780	85	70	4170	301	138
26Aug71	6	75	1730	43	30	4160	292	153
28Aug71	6	75	1930	32	29	4310	322	132
29Aug71	6	63	1750	17	15	4410	258	102
30Aug71	6	82	1930	26	25	4960	277	108
31Aug71	6	155	1840	26	23	4650	454	120
5Sep71	6	87	2030	20	20	4170	306	150
6Sep71	6	79	1800	30	29	3870	293	132
9Sep71	6	67	1660	12	12	3850	281	108
11Sep71	6	59	1470	10	7	3650	279	72
12Sep71	6	69	1530	14	13	3550	328	120
13Sep71	6	57	1350	19	17	3410	308	90
14Sep71	6	48	1610	22	19	3180	313	135
16Sep71	6	84	1700	40	37	3470	314	132
17Sep71	6	80	1690	31	27	3660	267	138
19Sep71	6	88	1820	21	18	4270	278	102
20Sep71	6	88	1870	27	22	4120	313	108

Date	Secondary effluent total COD, mg/l	Secondary effluent soluble COD, mg/l	Secondary effluent total BOD, mg/l	Secondary effluent soluble BOD, mg/l	Primary effluent flowrate, m^3/hr	Return sludge flowrate, m^3/hr	Waste sludge flowrate, m^3/hr	Aeration tank volume, m^3
19May71	92	70	7	6	136	67	2.2	240
20May71	75	64	8	7	136	81	2.2	240
21May71	92	103	8	8	136	78	2.2	240
23May71	80	64	14	10	136	81	2.1	240
24May71	101	79	14	11	136	79	2.1	240
25May71	124	70	34	10	136	74	2.5	240
28May71	121	71	16	4	142	73	2.5	240
29May71	109	76	16	6	142	48	2.5	240
16Aug71	112	80	24	12	250	215	7.1	240
17Aug71	113	81	16	5	248	215	5.3	240
20Aug71	142	74	39	13	237	176	3.6	240
23Aug71	97	70	32	17	242	170	2.7	240
24Aug71	108	59	52	20	235	170	3.9	240
25Aug71	150	75	38	15	250	170	4.2	240
26Aug71	103	70	34	17	245	170	3.7	240
28Aug71	93	66	25	13	266	170	4.0	240
29Aug71	86	70	18	14	256	170	4.0	240
30Aug71	87	71	21	17	243	170	4.4	240
31Aug71	81	70	12	7	251	170	4.3	240
5Sep71	66	60	38	13	253	159	4.4	240
6Sep71	76	60	27	18	236	159	4.2	240
9Sep71	81	54	21	12	246	148	4.3	240
11Sep71	89	79	11	11	253	153	4.5	240
12Sep71	98	71	21	11	242	153	4.2	240
13Sep71	99	77	19	10	245	148	4.3	240
14Sep71	77	53	28	13	246	150	4.4	240
16Sep71	81	54	21	11	249	148	4.0	240
17Sep71	96	59	31	18	249	148	3.9	240
19Sep71	67	50	19	13	248	148	3.9	240
20Sep71	82	66	14	9	246	148	3.8	240

Table 5 (continued). SUMMARY OF STEADY-STATE MEASUREMENTS

Date	Steady-state period	Primary effluent VSS, mg/l	MLVSS, mg/l	Secondary effluent TSS, mg/l	Secondary effluent VSS, mg/l	Return sludge VSS, mg/l	Primary effluent total COD, mg/l	Primary effluent total BOD, mg/l
28Sep71	7	79	1060	26	18	3030	337	153
29Sep71	7	84	1190	19	16	3120	358	120
10Oct71	7	240	1260	19	12	2950	582	156
30Oct71	7	49	1010	46	36	2690	307	120
40Oct71	7	63	1020	34	31	2690	319	78
50Oct71	7	71	830	35	27	2610	364	114
60Oct71	7	81	1080	17	13	2710	339	105
70Oct71	7	65	1140	19	18	2850	380	96
90Oct71	7	72	840	41	20	2800	333	87
100Oct71	7	109	1050	12	11	2730	347	108
110Oct71	7	137	950	15	10	2550	395	144
9Nov71	8	88	3280	28	25	8620	408	113
10Nov71	8	106	3280	25	22	8870	382	116
14Nov71	8	59	2530	40	36	6840	317	88
23Nov71	8	61	2080	39	27	4830	321	96
24Nov71	8	60	1890	36	26	5330	303	79
25Nov71	8	96	2370	57	44	5740	332	111
26Nov71	8	81	2050	30	23	5780	328	114
29Nov71	8	29	1770	31	22	4450	276	79
1Jan72	9	205	1190	62	29	3060	491	150
2Jan72	9	104	1040	66	66	2570	365	152
5Jan72	9	99	960	114	97	1770	353	105
6Jan72	9	104	1280	65	57	3630	393	156
8Jan72	9	76	1050	74	67	3210	363	84
10Jan72	9	94	960	64	59	2380	363	128
12Jan72	9	92	1380	55	52	3150	404	113

Date	Secondary effluent total COD, mg/l	Secondary effluent soluble COD, mg/l	Secondary effluent total BOD, mg/l	Secondary effluent soluble BOD, mg/l	Primary effluent flowrate, m^3/hr	Return sludge flowrate, m^3/hr	Waste sludge flowrate, m^3/hr	Aeration tank volume m^3
28Sep71	112	86	34	18	250	136	5.6	240
29Sep71	107	80	23	14	250	136	5.6	240
10Oct71	109	71	23	11	252	136	5.6	240
30Oct71	120	78	19	14	239	125	5.5	240
40Oct71	120	84	23	12	248	125	5.7	240
50Oct71	127	85	26	20	234	125	5.4	240
60Oct71	101	77	23	12	240	125	5.6	240
70Oct71	114	84	19	13	238	127	5.5	240
90Oct71	89	71	23	14	241	127	5.7	240
100Oct71	114	102	21	17	237	127	5.6	240
110Oct71	-	108	—	27	234	127	5.7	240
9Nov71	152	115	36	24	233	136	1.4	240
10Nov71	141	110	32	20	260	136	1.5	240
14Nov71	156	102	29	18	251	131	1.4	240
23Nov71	126	89	31	13	235	134	1.3	240
24Nov71	128	85	37	14	237	136	1.3	240
25Nov71	137	95	32	20	234	136	1.3	240
26Nov71	148	106	41	25	236	136	1.3	240
29Nov71	146	119	28	21	237	134	1.3	240
1Jan72	187	88	41	17	253	131	4.9	240
2Jan72	152	79	50	19	249	131	4.1	240
5Jan72	168	82	46	21	200	136	4.0	240
6Jan72	174	107	48	28	234	148	4.1	240
8Jan72	214	109	28	21	250	108	4.1	240
10Jan72	196	106	30	24	173	108	4.1	240
12Jan72	152	117	18	15	250	114	4.1	240

Table 6. SUMMARY OF STEADY-STATE PERFORMANCE PARAMETERS

Date	Hydraulic residence time, θ, day	Mean cell age, θ_c, day	Removal velocity, q_{COD}[a]	Removal velocity, q_{BOD}[b]	Loading velocity, L_{vCOD}[c]	Loading velocity, L_{vBOD}[d]	COD removal efficiency, %	BOD removal efficiency, %	Steady-state period
16Dec70	0.215	37.2	0.347	0.281	0.494	0.308	73	91	1
17Dec70	0.215	32.6	0.329	0.278	0.532	0.332	62	84	1
18Dec70	0.215	63.5	0.234	0.366	0.468	0.413	50	89	1
19Dec70	0.215	40.9	0.249	0.104	0.411	0.137	61	76	1
20Dec70	0.215	25.7	0.257	0.176	0.382	0.206	67	86	1
21Dec70	0.215	41.1	0.290	0.242	0.429	0.273	68	89	1
31Dec70	0.215	14.2	0.367	0.312	0.737	0.347	50	90	1
2Jan71	0.215	24.8	0.560	0.173	0.696	0.198	80	87	1
3Jan71	0.215	21.3	0.450	0.172	0.613	0.200	73	86	1
5Jan71	0.215	22.7	0.560	0.184	0.656	0.200	85	92	1
15Jan71	0.172	12.3	0.542	0.253	0.849	0.285	64	89	2
16Jan71	0.172	14.2	0.551	0.296	0.777	0.318	71	93	2
17Jan71	0.174	29.7	0.305	0.268	0.448	0.292	68	92	2
18Jan71	0.174	10.2	0.270	0.314	0.413	0.334	65	94	2
15Apr71	0.110	3.06	0.619	0.250	0.795	0.267	78	94	3
16Apr71	0.117	3.62	0.676	0.260	0.895	0.279	76	93	3
18Apr71	0.103	3.05	0.592	0.206	0.793	0.225	75	92	3
19Apr71	0.103	2.98	0.783	0.178	1.00	0.207	78	86	3
9May71	0.071	1.44	1.20	0.613	1.58	0.649	76	94	4
11May71	0.067	1.55	1.49	0.593	1.96	0.654	76	91	4
12May71	0.076	1.32	2.04	0.942	2.41	1.01	84	93	4
13May71	0.075	2.10	2.26	0.725	2.70	0.762	84	95	4
14May71	0.076	1.46	1.90	0.572	2.44	0.636	78	90	4
16May71	0.076	1.42	1.28	0.443	1.67	0.455	77	93	4
17May71	0.073	1.40	1.42	0.485	1.79	0.541	79	90	4
18May71	0.076	1.92	1.71	0.504	2.14	0.563	80	90	4

Table 6 (continued). SUMMARY OF STEADY-STATE PERFORMANCE PARAMETERS

Date	Hydraulic residence time, θ, day	Mean cell age, θ_c, day	Removal velocity, q_{COD}[a]	q_{BOD}[b]	Loading velocity, L_{vCOD}[c]	L_{vBOD}[d]	COD removal efficiency, %	BOD removal efficiency, %	Steady-state period
19May71	0.073	1.36	1.53	0.499	1.91	0.481	80	93	5
20May71	0.073	1.35	1.83	0.567	2.19	0.606	84	94	5
21May71	0.073	1.51	2.56	0.693	3.11	0.736	82	94	5
23May71	0.073	1.57	1.96	0.754	2.28	0.803	86	94	5
24May71	0.073	1.57	1.66	0.718	2.04	0.771	81	93	5
25May71	0.073	1.29	1.78	0.812	2.16	0.868	82	94	5
28May71	0.070	1.27	2.76	0.519	3.16	0.542	87	96	5
29May71	0.070	1.20	1.76	0.625	2.23	0.661	79	94	5
16Aug71	0.040	0.545	3.42	1.41	4.46	1.57	76	90	6
17Aug71	0.040	0.625	2.37	1.01	3.29	1.07	72	95	6
20Aug71	0.042	0.700	2.70	1.25	3.68	1.42	73	88	6
23Aug71	0.041	0.788	3.63	1.78	4.57	2.01	79	89	6
24Aug71	0.043	0.692	3.15	1.62	4.06	1.92	78	84	6
25Aug71	0.040	0.508	3.18	1.73	4.24	1.94	75	89	6
26Aug71	0.040	0.754	3.20	1.96	4.20	2.20	76	89	6
28Aug71	0.038	0.776	3.53	1.64	4.44	1.82	80	90	6
29Aug71	0.030	0.817	2.75	1.29	3.77	1.49	73	86	6
30Aug71	0.041	0.753	2.60	1.45	3.49	1.36	74	84	6
31Aug71	0.040	0.715	5.23	1.54	6.19	1.64	84	94	6
5Sep71	0.039	0.874	3.07	1.71	3.82	1.87	81	91	6
8Sep71	0.042	0.775	3.07	1.50	3.86	1.74	80	86	6
9Sep71	0.041	0.848	3.37	1.43	4.17	1.60	81	89	6
11Sep71	0.039	0.812	3.44	1.05	4.80	1.24	72	88	6
12Sep71	0.041	0.411	4.08	1.73	5.20	1.90	78	91	6
13Sep71	0.041	0.719	4.20	1.46	5.60	1.64	75	89	6
14Sep71	0.041	0.871	3.94	1.86	4.78	2.06	82	90	6
16Sep71	0.040	0.740	3.82	1.78	4.61	1.94	83	92	6
17Sep71	0.040	0.806	3.07	1.77	3.95	2.04	78	87	6
19Sep71	0.040	0.860	3.12	1.22	3.80	1.39	82	87	6

Table 6 (continued). SUMMARY OF STEADY-STATE PERFORMANCE PARAMETERS

Date	Hydraulic residence time, θ, day	Mean cell age, θ_c, day	Removal velocity, q_{COD}[a]	Removal velocity, q_{BOD}[b]	Loading velocity, L_{vCOD}[c]	Loading velocity, L_{vBOD}[d]	COD removal efficiency, %	BOD removal efficiency, %	Steady-state period
20Sep71	0.041	0.881	3.26	1.31	4.13	1.42	79	92	6
28Sep71	0.040	0.493	5.96	3.21	8.01	3.64	74	88	7
29Sep71	0.040	0.556	5.88	2.24	7.57	2.53	78	88	7
10ct71	0.040	0.649	10.2	2.90	11.7	3.13	88	93	7
30ct71	0.042	0.434	5.40	2.50	7.24	2.83	75	88	7
40ct71	0.040	0.337	5.73	1.61	7.78	1.90	74	85	7
50ct71	0.043	0.482	6.64	2.24	8.67	2.71	77	82	7
60ct71	0.042	0.590	5.86	2.08	7.58	2.35	77	88	7
70ct71	0.042	0.569	6.19	1.74	7.95	2.01	78	86	7
90ct71	0.041	0.407	7.52	2.10	9.56	2.50	79	84	7
100ct71	0.042	0.589	5.55	2.06	7.86	2.44	71	84	7
110ct71	0.042	0.562	7.24	2.95	9.96	3.63	73	81	7
9Nov71	0.039	1.81	2.29	0.697	3.19	0.885	72	79	8
10Nov71	0.038	1.74	2.16	0.762	3.03	0.921	71	83	8
14Nov71	0.040	1.38	2.14	0.696	3.15	0.874	68	80	8
23Nov71	0.042	1.63	2.63	0.940	3.63	1.09	72	86	8
24Nov71	0.042	1.44	2.74	0.815	3.80	0.991	72	82	8
25Nov71	0.043	1.35	2.34	0.900	3.28	1.11	71	82	8
26Nov71	0.042	1.60	2.56	1.03	3.78	1.32	68	78	8
29Nov71	0.042	1.60	2.11	0.778	3.70	1.06	57	73	8
1Jan72	0.039	0.538	8.57	2.83	10.4	3.19	82	89	9
2Jan72	0.040	0.388	6.86	3.19	8.76	3.65	78	88	9
5Jan72	0.050	0.364	5.69	1.76	7.42	2.21	77	80	9
6Jan72	0.043	0.456	5.24	2.34	7.20	2.86	73	82	9
8Jan72	0.040	0.353	6.06	1.50	8.66	2.00	70	75	9
10Jan72	0.058	0.486	4.64	1.88	6.55	2.31	71	81	9
12Jan72	0.040	0.535	5.21	1.78	7.34	2.05	71	87	9

[a] (mg COD removed)/(mg MLVSS)(day). [b] (mg BOD removed)/(mg MLVSS)(day).
[c] (mg COD applied)/(mg MLVSS)(day). [d] (mg BOD applied)/(mg MLVSS)(day).

concentration depends solely on the performance of the solids separation system, effluent soluble substrate concentration was assumed to be the limiting substrate concentration for the kinetic analysis.

Secondary Effluent Quality

As mentioned previously, the secondary effluent substrate and solids concentrations depend on the growth characteristics of the activated sludge and the solids separation system performance, respectively. In this study, because the system was deliberately operated from a very low-rate system to a high-rate system, the secondary effluent substrate concentration varied with the system growth rate. Secondary effluent total BOD concentrations (Table 5) varied widely from 7 to 61 mg/l and no consistent trend could be delineated. However, secondary effluent soluble BOD (Table 5) varied from 4 to 28 mg/l and appeared to be a function of system growth rate. This relationship will be discussed subsequently in the kinetic analysis section.

Secondary effluent total suspended solids in this study ranged from 2 to 114 mg/l and volatile suspended solids varied from 2 to 97 mg/l (Table 5), despite the use of low--13 $m^3/(m^2)(day)$[315 $gal/(ft^2)(day)$]--overflow rates in the secondary clarifier. No correlation could be drawn between secondary effluent total or volatile suspended solids and system growth characteristics. The relationship between secondary effluent solids concentration and solids separation system performance will be discussed subsequently under the evaluation of solids separation systems.

Active Biomass Parameters--ATP and Dehydrogenase Activity

In addition to the mixed liquor volatile suspended solids (MLVSS), adenosine triphosphate (ATP) and dehydrogenase activity (measured as triphenyl formazan, TF, formed per hour) were used to estimate the active biomass concentration. Although complete daily ATP and dehydrogenase activity measurements were not conducted throughout the study period, 11 steady-state ATP and dehydrogenase activity measurements were performed, and are reported in Table 7.

Table 7. STEADY-STATE ACTIVE ORGANISM CONCENTRATION MEASUREMENTS

Date	Steady-state period	ATP/MLVSS, (μg ATP)/(mg MLVSS)	Dehydrogenase/MLVSS, (μg TF)/(mg MLVSS)(hr)	Effluent soluble COD, mg/l	Effluent soluble BOD, mg/l
18 May 71	4	0.47	52.6	72	10
19 May 71	5	0.58	27.7	70	6
24 May 71	5	0.49	37.4	79	11
25 May 71	5	0.51	43.7	70	10
17 Aug 71	6	0.78	54.6	81	5
24 Aug 71	6	0.72	32.6	59	20
28 Aug 71	6	0.80	42.1	66	13
4 Oct 71	7	1.02	73.7	84	12
5 Jan 72	9	1.22	68.0	82	21
6 Jan 72	9	1.24	50.4	107	28
10 Jan 72	9	1.01	72.6	106	24

Previous research studies (References 21 and 22) have reported ATP content and dehydrogenase activity of activated sludge as viability measurements. These studies found that the ATP content ranged from 0.2 to 0.3 (μg ATP)/(mg MLVSS) (Reference 21) and dehydrogenase activity ranged from 31 to 83 (mg TF)/(g MLVSS)(hr) (Reference 22). The ATP content of the MLVSS in this study [0.47 to 1.24 (μg ATP)/(mg MLVSS)] was higher than previously reported values, while the dehydrogenase activities [27.7 to 73.7 (μg TF)/(mg MLVSS)(hr)] were about the same as the values reported by Ford, *et al.* (Reference 22).

ATP and dehydrogenase activity measurements were used in the kinetic analyses and the performance characteristics based on ATP and dehydrogenase activity are listed in Table 8. These characteristics included substrate (BOD and COD) removal velocity based on ATP and dehydrogenase activity, net growth rate and effluent soluble substrate (BOD and COD) concentrations.

KINETIC ANALYSIS AND KINETIC CONSTANTS

The kinetic characteristics of the accelerated high-rate activated sludge system were evaluated with respect to the following equations and kinetic coefficients and constants:

(1) The cell continuity equation,

$$1/\theta_c = Yq - k_d$$

where Y = yield coefficient

k_d = decay constant.

(2) Michaelis-Menten (Monod) equation,

$$q = \frac{\hat{q}\, S_1}{K_s + S_1}$$

where $\hat{q}_{BOD}$ = maximum BOD removal velocity

$\hat{\mu} = Y\hat{q}$ = maximum specific growth rate

K_s = half-saturation constant.

Table 8. STEADY-STATE PERFORMANCE CHARACTERISTICS BASED ON ATP AND DEHYDROGENASE ACTIVITY

Date	Steady-state period	$q_{COD(ATP)}$, $\frac{\text{(mg COD removed)}}{\text{(µg ATP)(day)}}$	$q_{BOD(ATP)}$, $\frac{\text{(mg BOD removed)}}{\text{(µg ATP)(day)}}$	$q_{COD(TF)}$, $\frac{\text{(mg COD removed)}}{\text{(µg TF/hr)(day)}}$	$q_{BOD(TF)}$, $\frac{\text{(mg BOD removed)}}{\text{(µg TF/hr)(day)}}$	$1/\theta_c$, day^{-1}
18 May 71	4	3.64	1.07	0.0326	0.00958	0.521
19 May 71	5	2.64	0.774	0.0554	0.0162	0.738
24 May 71	5	3.38	1.47	0.0443	0.0192	0.638
25 May 71	5	3.48	1.59	0.0406	0.0186	0.774
17 Aug 71	6	3.04	1.29	0.0434	0.0185	1.60
24 Aug 71	6	4.38	2.25	0.0967	0.0498	1.45
28 Aug 71	6	4.42	2.05	0.0839	0.0390	1.29
4 Oct 71	7	5.62	1.58	0.0777	0.0218	2.24
5 Jan 72	9	4.67	1.45	0.0837	0.0260	2.75
6 Jan 72	9	4.23	1.89	0.104	0.0465	2.19
10 Jan 72	9	4.59	1.86	0.0639	0.0259	2.06

(3) Modified Michaelis-Menten (Monod) equation,

$$q = \frac{\hat{q}(S_1 - K_{COD})}{(K_s - K_{COD}) + (S_1 - K_{COD})}$$

where $\hat{q}_{COD}$ = maximum COD removal velocity

$\hat{\mu} = Y\hat{q}$ = maximum specific growth rate

K_s = half-saturation constant

K_{COD} = nonbiodegradable COD concentration.

Evaluation of Cell Continuity Equation

The cell continuity equation, $1/\theta_c = Yq - k_d$, was used to estimate the yield coefficient and decay constant. Two substrate measures, BOD and COD, were used as substrate parameters, and the active biomass concentration parameters were expressed as mixed liquor volatile suspended solids, ATP content and dehydrogenase activity.

MLVSS as Active Biomass Parameter--

Least-square regression analyses of all steady-state measurements resulted in a yield coefficient of 0.793 (mg MLVSS produced)/(mg BOD removed), as shown in Figure 4, and 0.293 (mg MLVSS produced)/(mg COD removed), as shown in Figure 5. Although reasonable estimates of yield coefficients were obtained with highly significant correlation coefficients (R = 0.865 for BOD basis and 0.871 for COD basis), relatively high negative decay constants were obtained (k_d = -0.119 and -0.164 day^{-1} based on BOD and COD, respectively). From a statistical regression standpoint, one of the primary causes for the negative k_d appears to be the widely scattered data points for net growth rates greater than 1.6 day^{-1} (*cf.* Figures 4 and 5). Consequently, the total variation, *i.e.*, the sum of the squares of the deviation of the values of net growth rate from the mean net growth rate value, of these data points could markedly affect both the slope (yield coefficient) and the intercept (decay constant) of the cell continuity equation (Equation 16).

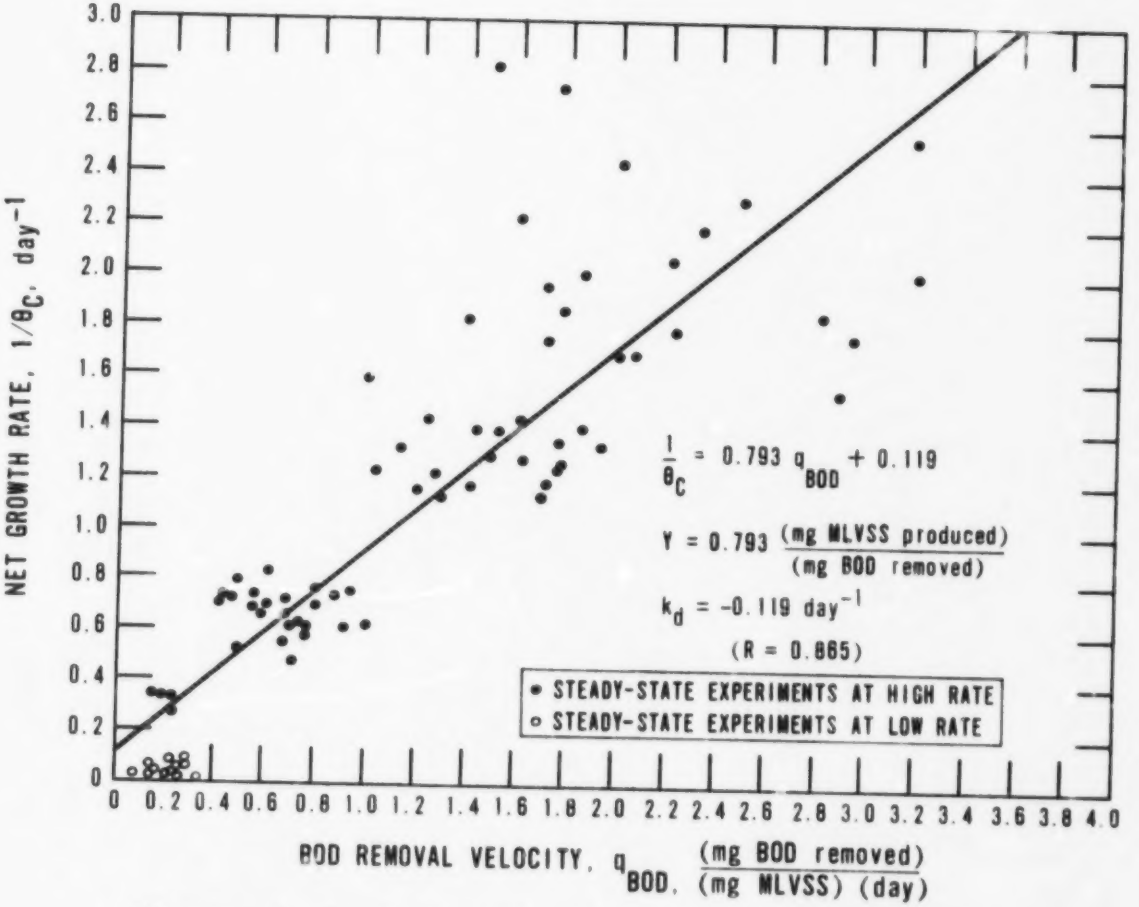

NET GROWTH RATE, $1/\theta_C$, day^{-1}
BOD REMOVAL VELOCITY, q_{BOD}, $\frac{\text{(mg BOD removed)}}{\text{(mg MLVSS) (day)}}$
$\frac{1}{\theta_C} = 0.793\ q_{BOD} + 0.119$
$Y = 0.793\ \frac{\text{(mg MLVSS produced)}}{\text{(mg BOD removed)}}$
$k_d = -0.119$ day^{-1}
(R = 0.865)
• STEADY-STATE EXPERIMENTS AT HIGH RATE
○ STEADY-STATE EXPERIMENTS AT LOW RATE

Figure 4 Plot of cell continuity equation using BOD as substrate parameter

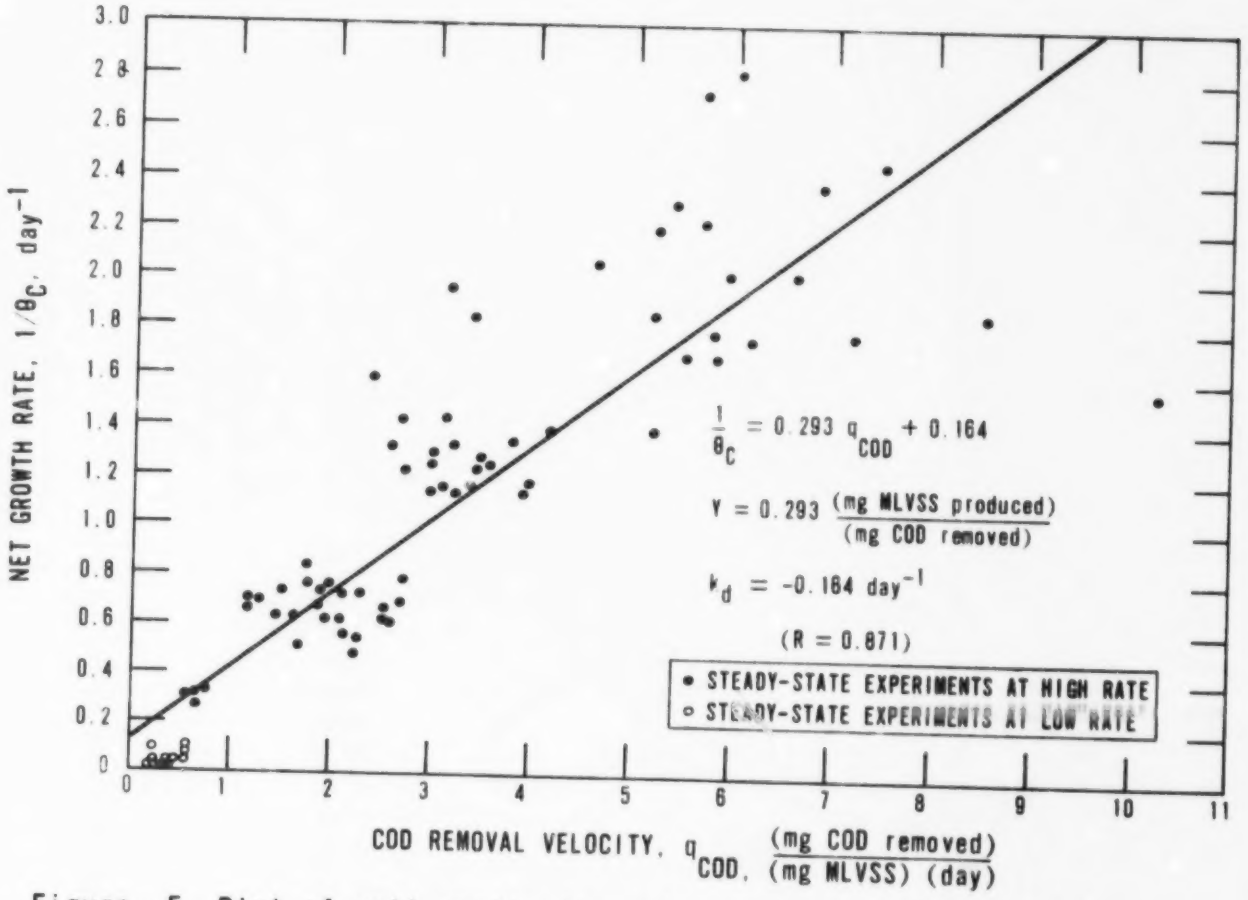

NET GROWTH RATE, $1/\theta_C$, day^{-1}
COD REMOVAL VELOCITY, q_{COD}, $\frac{(mg\ COD\ removed)}{(mg\ MLVSS)\ (day)}$
$\frac{1}{\theta_C} = 0.293\ q_{COD} + 0.164$
$Y = 0.293\ \frac{(mg\ MLVSS\ produced)}{(mg\ COD\ removed)}$
$k_d = -0.164\ day^{-1}$
(R = 0.871)
• STEADY-STATE EXPERIMENTS AT HIGH RATE
○ STEADY-STATE EXPERIMENTS AT LOW RATE

Figure 5. Plot of cell continuity using COD as substrate parameter

To check this possibility, regression analyses were made on mean values of nine steady-state periods. Yield coefficients of 0.922 (mg MLVSS produced)/(mg BOD removed), as shown in Figure 6, and 0.328 (mg MLVSS produced)/(mg COD removed), as shown in Figure 7, were obtained with identical, highly significant correlations ($R = 0.981$, $p > 0.99$). These values of yield coefficients are within the range reported by many workers (References 23, 24 and 25) From the reported data, it appears that the yield coefficients of 0.50 to 0.97 (mg MLVSS)/(mg BOD removed) and 0.32 to 0.46 (mg MLVSS)/(mg COD removed) are applicable to the activated sludge treatment system of domestic wastewater.

Corresponding values of decay constants in the cell continuity equation (Figures 6 and 7) were found to be 0.027 and -0.023 day^{-1} based on BOD and COD, respectively. The decay constant of 0.027 day^{-1} based on BOD is of the same magnitude as reported decay rates. Heukelekian *et al.* (Reference 26) reported a decay rate for activated sludge of 0.055 day^{-1} and Jenkins and Menar (Reference 25) reported a decay rate of 0.015 day^{-1}.

The negative decay value, -0.023 day^{-1} based on COD, appears to be questionable, although negative values for decay rates have been reported for bacterial systems (References 23 and 27). Theoretically, according to the cell continuity equation, the value of k_d should be positive rather than negative. The possibilities of varying decay rates and varying yield coefficients caused by the temperature variation in mixed liquor (17 to 26°C) through the 15-month study period may have caused a negative k_d to result upon linear regression analysis. No attempt was made to evaluate the effect of temperature on these kinetic characteristics due to limited and incomplete data.

ATP and Dehydrogenase as Active Biomass Parameters

The yield coefficients and decay rates based on 11 ATP and dehydrogenase activity measurements were obtained from regression analysis of the cell continuity equation, which are presented in Figures 8, 9, 10 and 11.

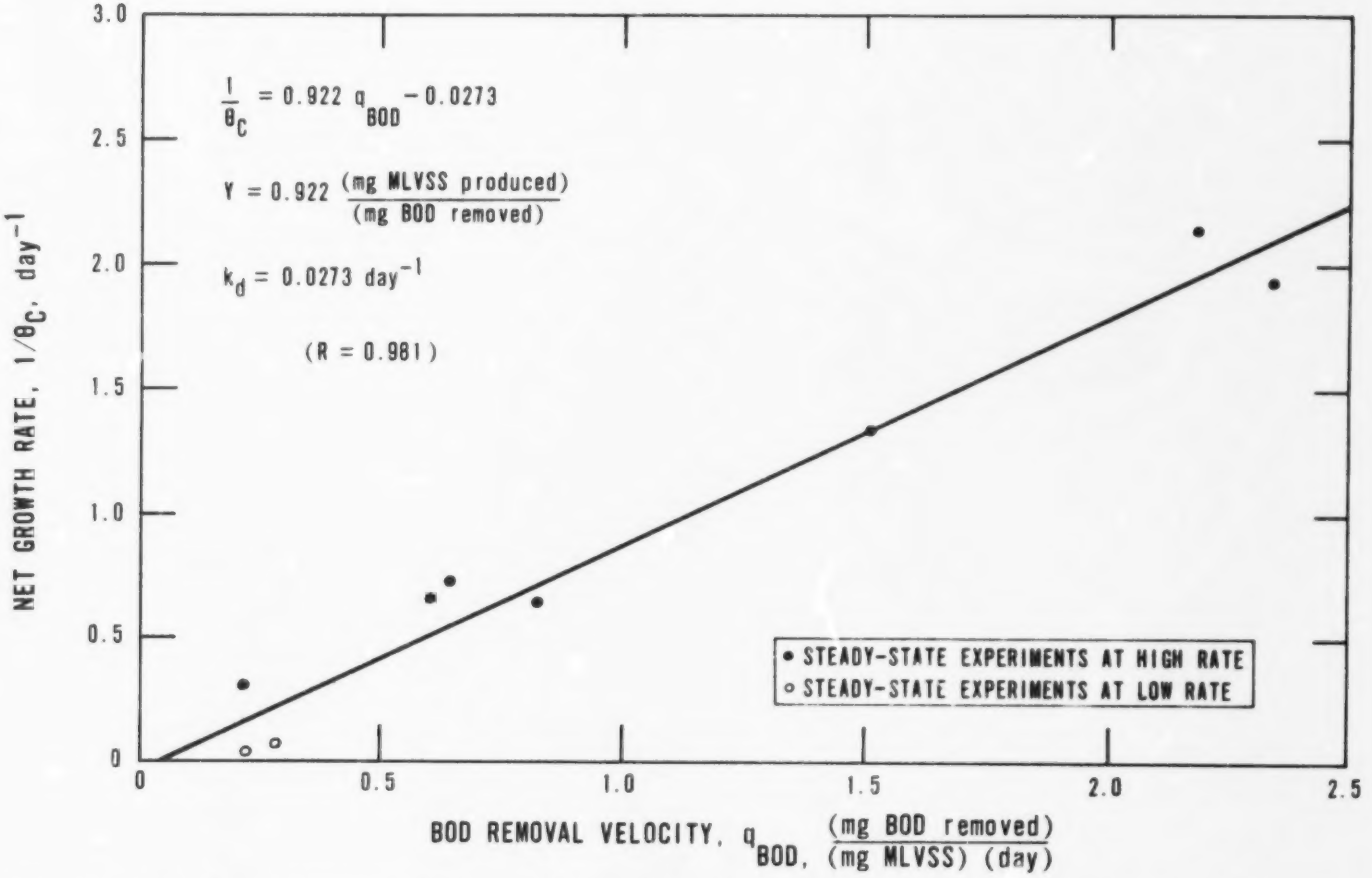


Figure 6 Cell continuity equation for mean steady-state values using BOD as substrate parameter

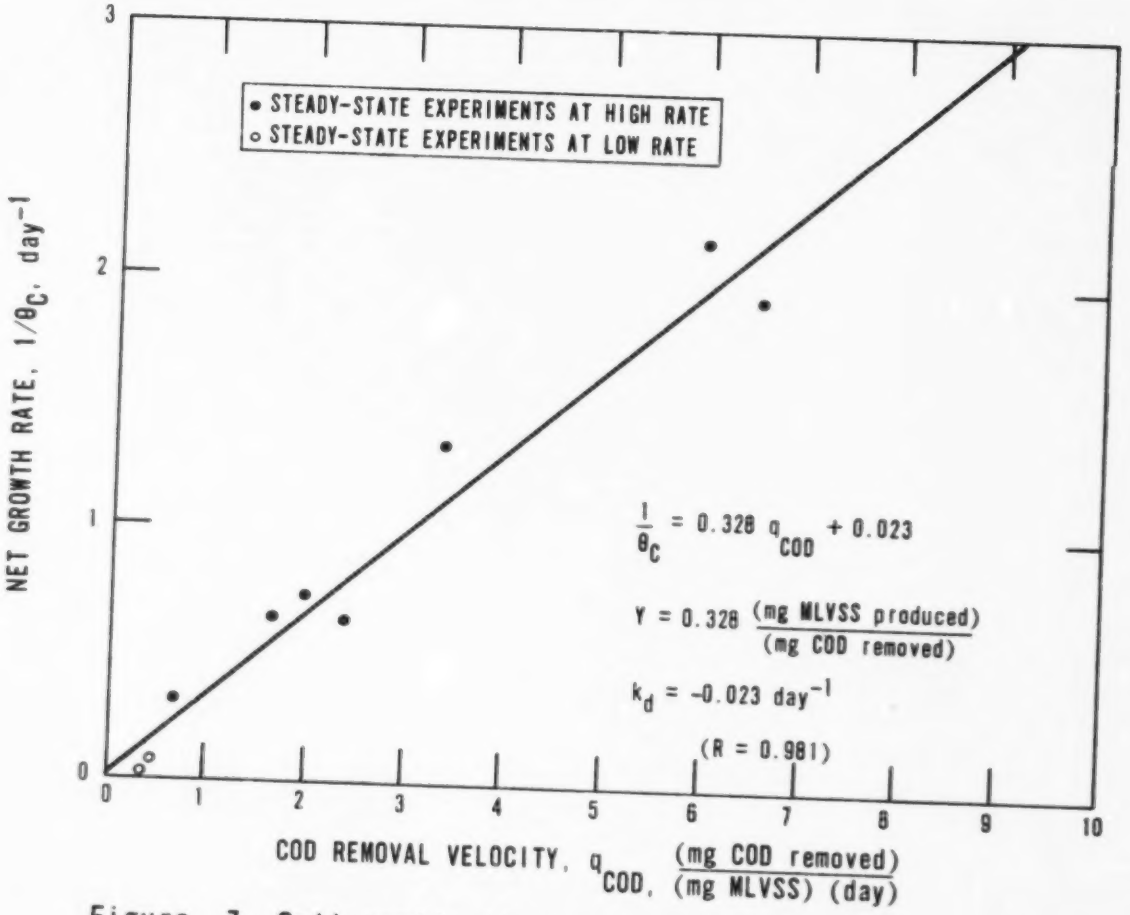


Figure 7 Cell continuity equation for mean steady-state values using COD as substrate parameter

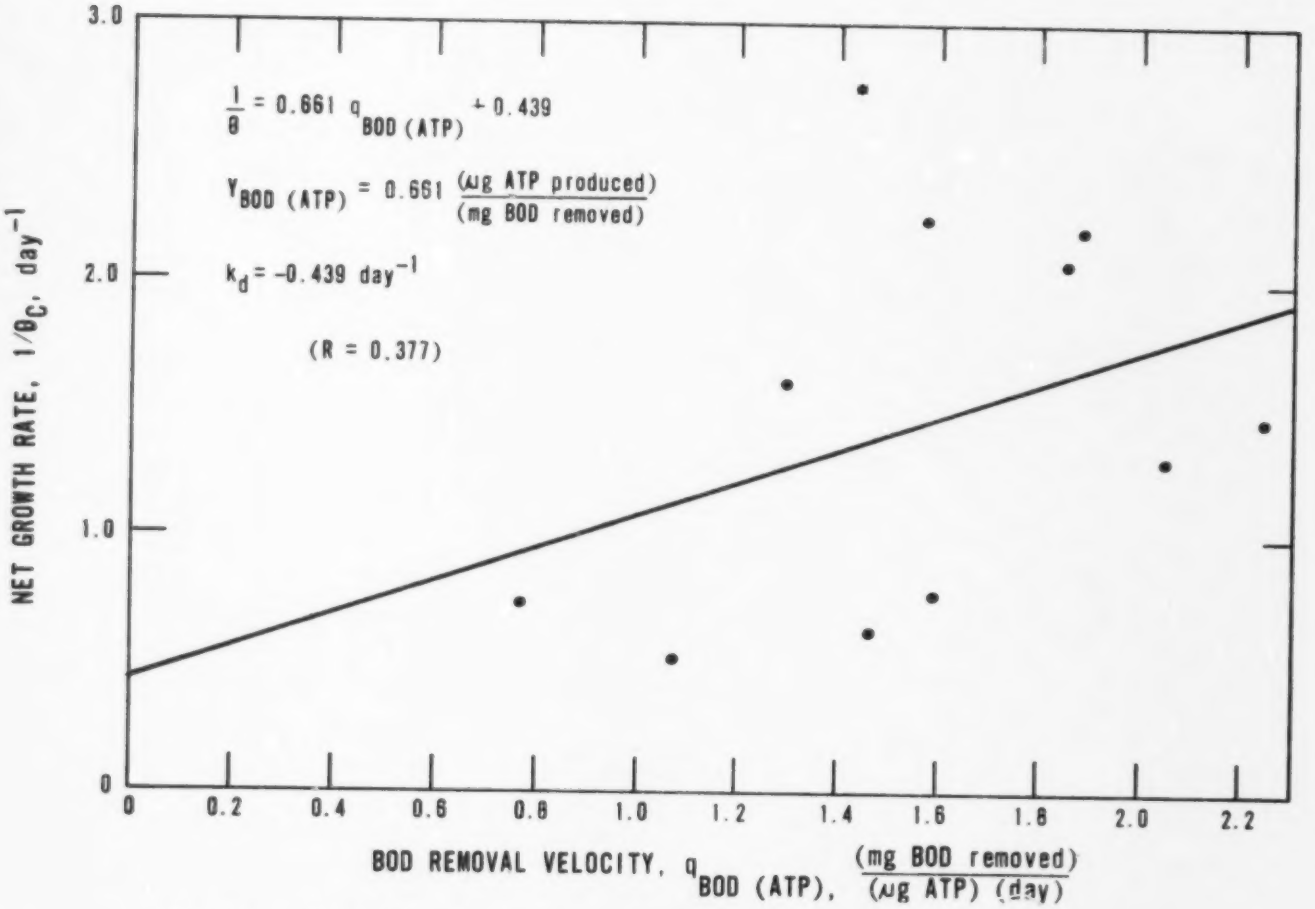


Figure 8 Plot of cell continuity equation using BOD and ATP

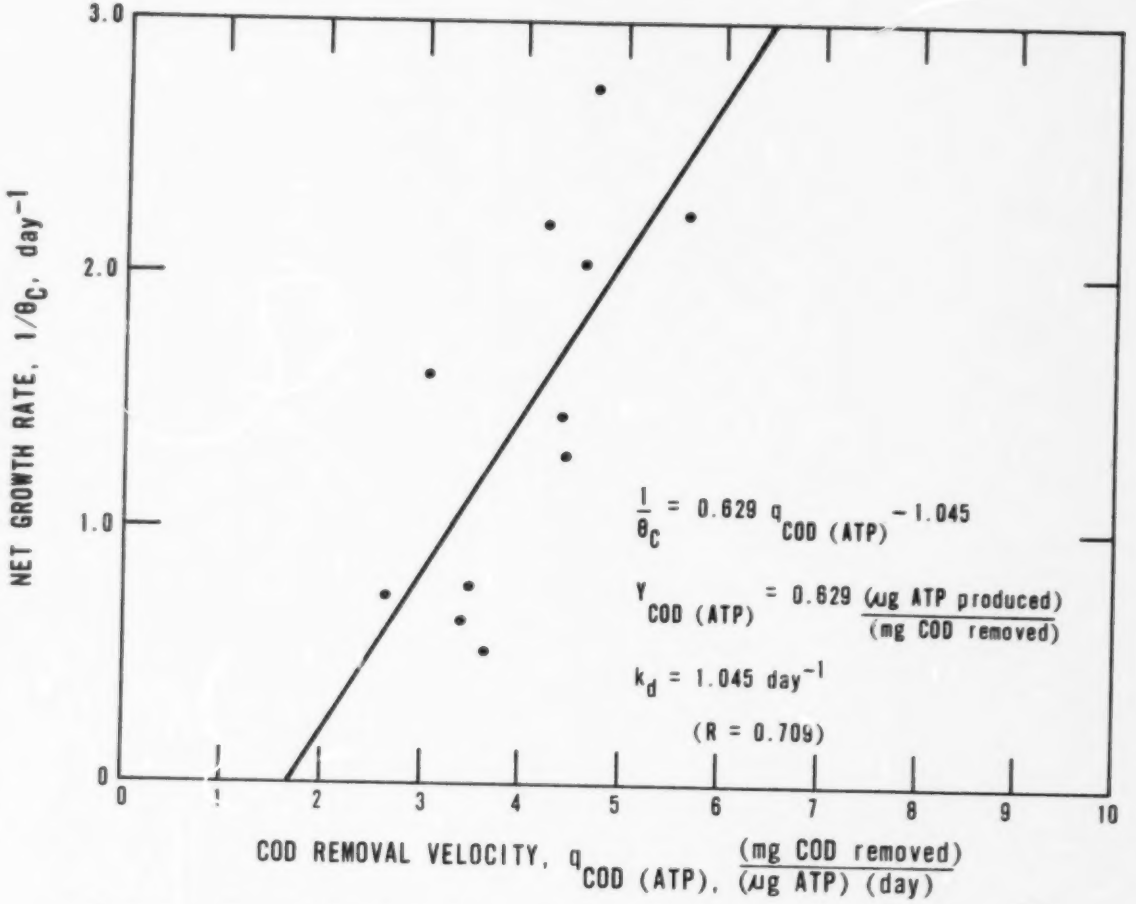


Figure 9 Plot of cell continuity equation using COD and ATP

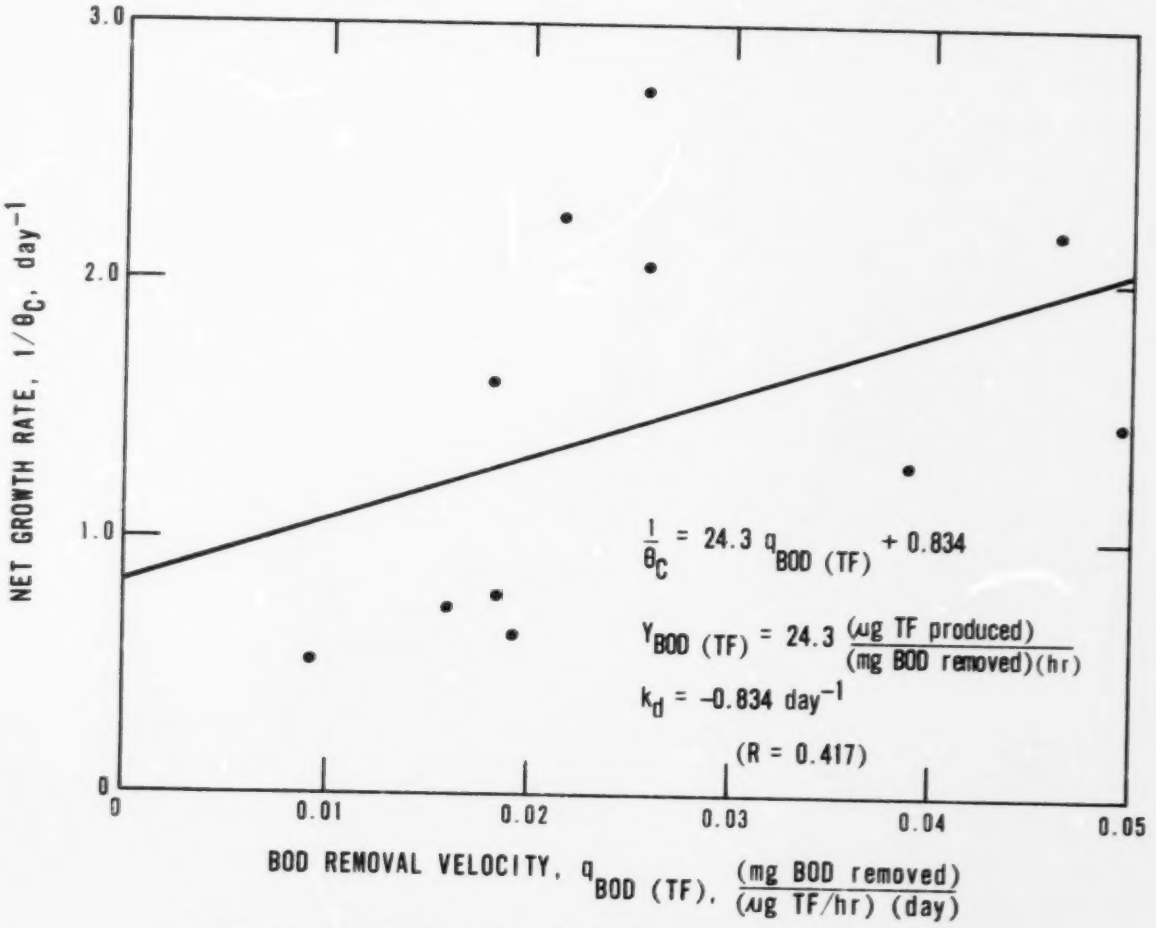


Figure 10 Plot of cell continuity equation using BOD and dehydrogenase activity

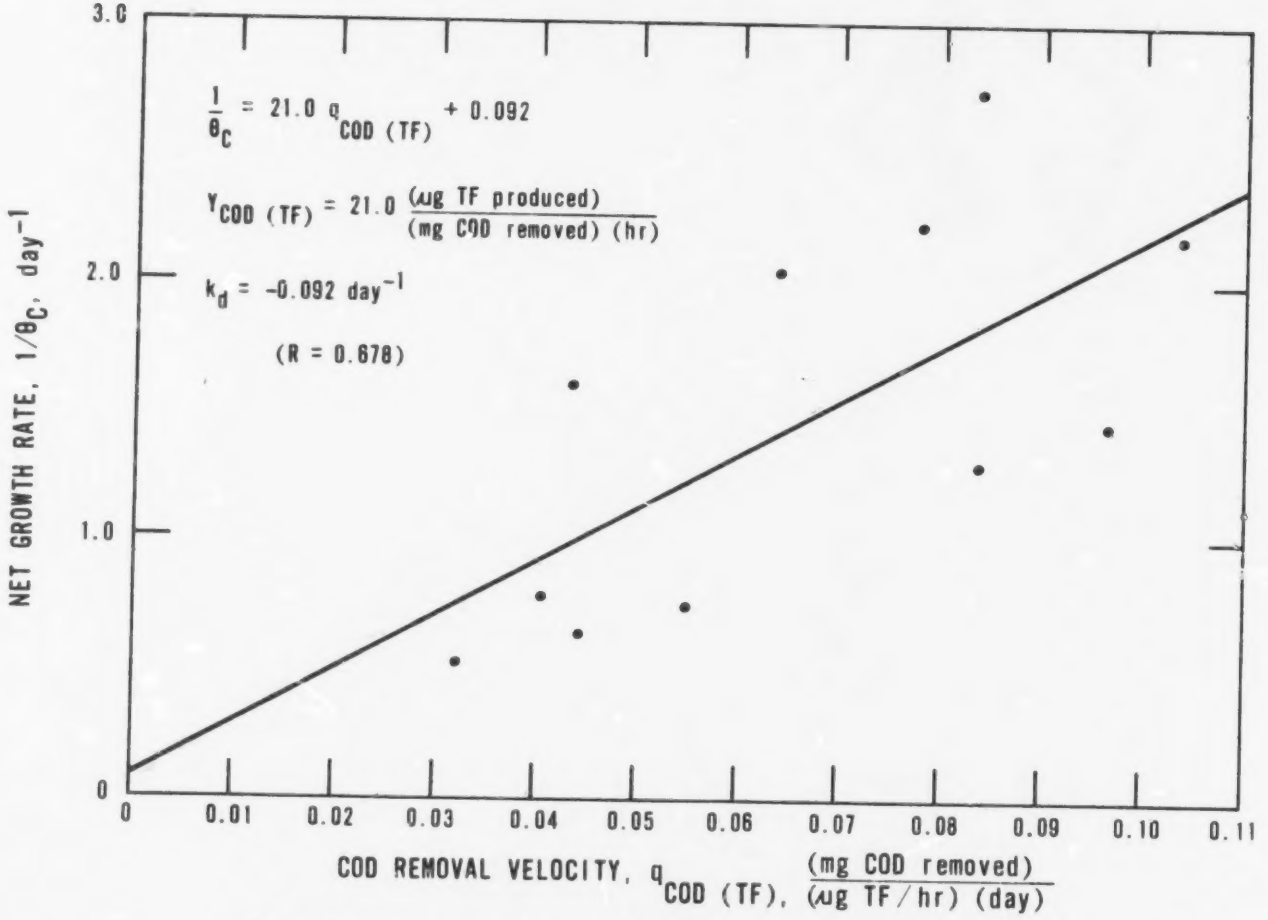


Figure 11 Plot of cell continuity equation using COD and dehydrogenase activity

Based on ATP measurements, as shown in Figure 8, a yield coefficient of 0.661 (μg TF produced)/(mg BOD removed) and a decay rate of -0.439 day^{-1} were observed with a poor correlation coefficient (R = 0.377). Using COD as the substrate measure, as shown in Figure 9, a yield coefficient of 0.629 (μg ATP produced)/(mg COD removed) and a large positive decay of 1.045 day^{-1} were obtained, with good correlation (R = 0.709).

Poor correlation was observed using dehydrogenase activity as an active biomass measure, as shown in Figure 10. A yield coefficient of 24.3 (μg TF produced)/(mg BOD removed)(hr) and a decay rate of -0.834 day^{-1} were obtained (R = 0.417). A good correlation (R = 0.678), however, existed for the cell continuity equation based on dehydrogenase activity and COD removal velocity, as shown in Figure 11. The yield coefficient and decay rate were 21.0 (μg TF produced)/(mg COD removed)(hr) and -0.092 day^{-1}, respectively.

Evaluation of Substrate Removal Velocity and Substrate Concentration Relationships

Two different approaches were used to evaluate the substrate removal velocity and substrate concentration relationships. These approaches were:

(1) By direct nonlinear regression analysis of the Michaelis-Menten (Monod) relationship, $q = \hat{q}S_1/(K_s + S_1)$, to determine the maximum BOD removal velocity, $\hat{q}$, and half-saturation constant constant, K_s, and

(2) By direct nonlinear regression analysis of a modified Michaelis-Menten (Monod) equation, assuming a certain fraction of the COD is nonbiodegradable, namely,

$$q = \frac{\hat{q}(S_1 - K_{COD})}{(K_s - K_{COD}) + (S_1 - K_{COD})} \qquad (34)$$

where K_{COD} = nonbiodegradable COD concentration.

To evaluate the Michaelis-Menten (Monod) kinetic model and its modified equation (Equation 34), all steady-state measurements were used in the regression analyses. A poor correlation and unreasonable estimate of kinetic constants resulted, however, primarily due to wide scatter in the data points, especially for measurements at low removal rates. It appears that different activated sludge cultures (groups of microorganisms) were predominant at the different growth/removal rates. This appeared to be significant in this study because of the wide range of removal rates studied. One would expect to observe different kinetic characteristics for cultures grown at widely different rates. Because one of the specific objectives of this study was to evaluate the kinetic characteristics of the accelerated high-rate activated sludge system, measurements obtained at low growth rates (Steady-State Periods 1 and 2) were excluded from the following kinetic evaluation.

Michaelis-Menten (Monod) Equation--

By direct nonlinear regression analysis of steady-state measurements, a maximum BOD removal rate of 4.13 (mg BOD removed)/(mg MLVSS)(day), and a half-saturation constant of 26.4 (mg BOD)/l were obtained, as shown in Figure 12. Multiplication of this maximum BOD removal velocity by the yield coefficient [0.922(mg MLVSS)/(mg BOD removed)] produces a maximum specific growth rate of 3.81 day^{-1} on a BOD basis. These estimates of $\hat{q}$, K_s and $\hat{\mu}$ appear to be both realistic and representative of the accelerated high-rate activated sludge system, where a high BOD removal rate and high maximum specific growth rate would be expected. The low value of the half-saturation constant, K_s, of 26.4 (mg BOD)/l indicates that organic matter was the limiting factor in the system and BOD appears to be an excellent parameter of the biodegradable substrate.

Based on ATP as the active biomass parameter, direct nonlinear regression analysis of 11 steady-state measurements, presented in Figure 13, yielded a maximum BOD removal velocity of 2.30 (mg BOD removed)/(µg ATP)(day), and a half-saturation constant of 5.1 (mg BOD)/l. The corresponding maximum specific growth rate, $\hat{\mu}_{ATP}$, was found to be 1.52 day^{-1}, which is a low value. Similarly, kinetic constants $\hat{q}$, K_s, y and k_d, determined on an ATP basis, appear to be on the low side of expected values.

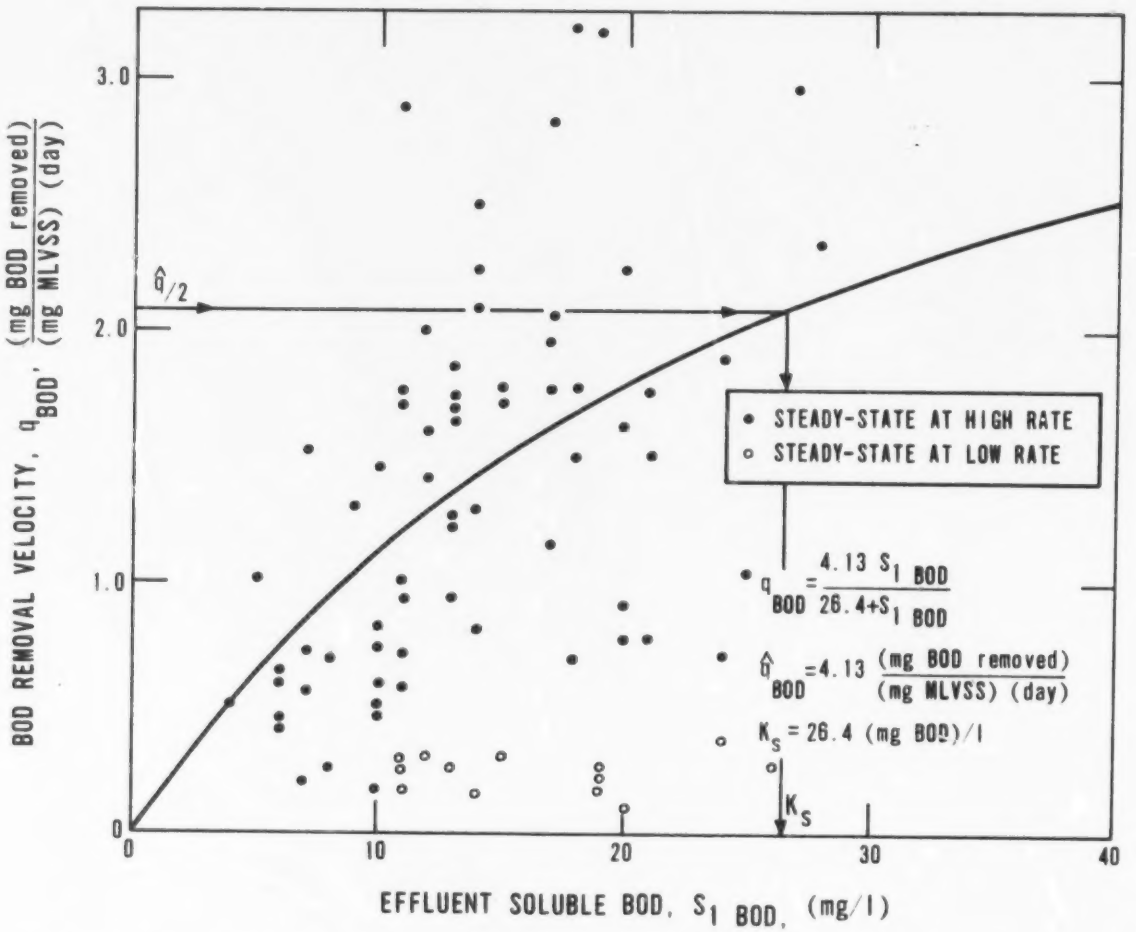


Figure 12 Plot of Michaelis-Menten (Monod) equation for accelerated high-rate activated sludge system using BOD as substrate parameter

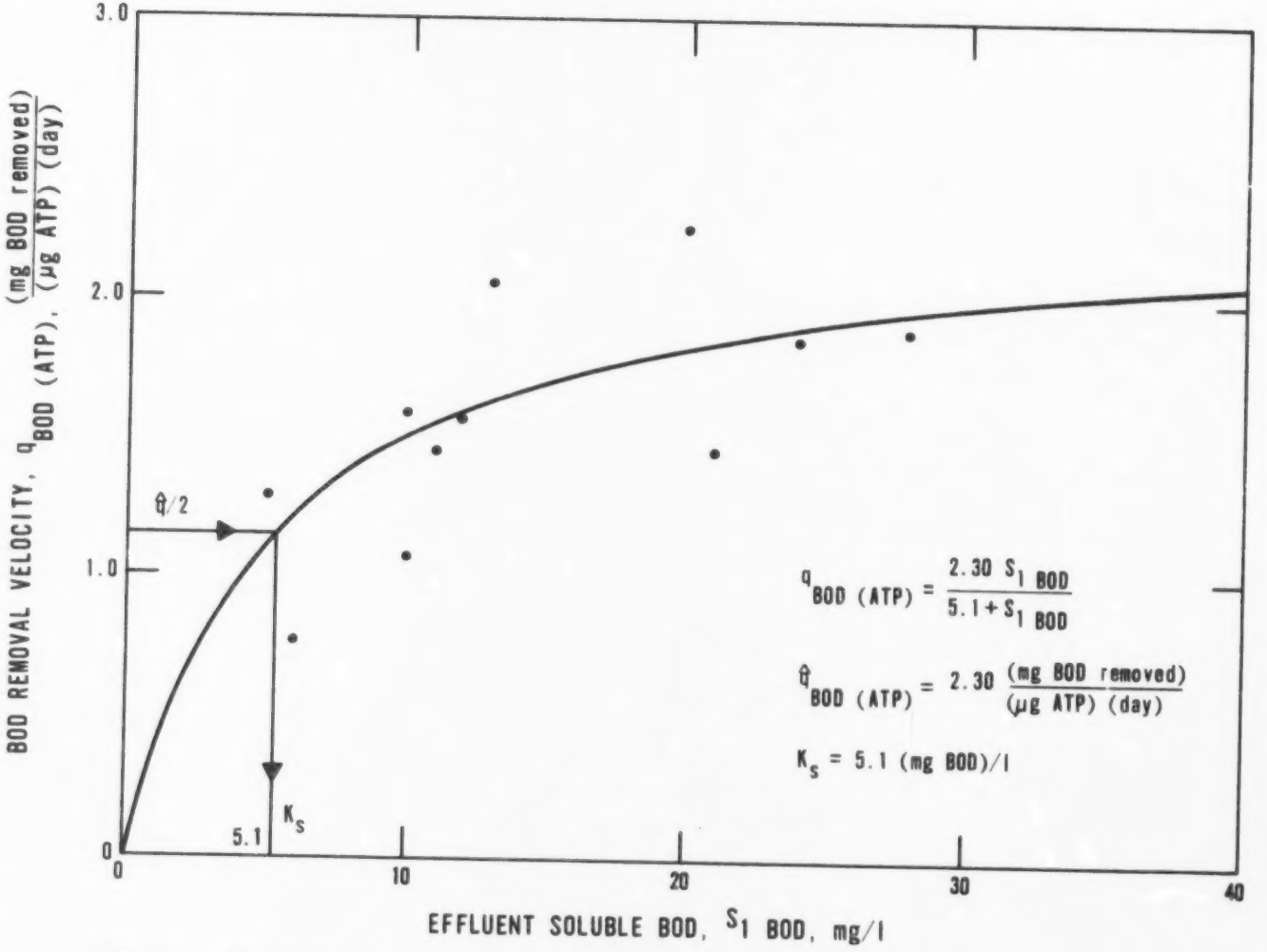


Figure 13 Plot of Michaelis-Menten (Monod) equation using BOD and ATP

Using dehydrogenase activity as an active biomass measure, a maximum BOD removal rate of 0.101 (mg BOD removal)/(μg TF/hr)(day) and a half-saturation constant of 39.9 (mg BOD)/l were obtained, as shown in Figure 14. The maximum specific growth rate based on dehydrogenase activity was estimated to be 2.45 day^{-1}. Because of scattered data and a limited number of data points, kinetic characteristics based on dehydrogenase activity were inconclusive.

Modified Michaelis-Menten (Monod) Equation

When COD was used as the substrate concentration parameter, a certain amount of COD, K_{COD}, was assumed to be nonbiodegradable to activated sludge.

Direct nonlinear regression analysis of the modified Michaelis-Menten (Monod) equation (Equation 34) gave a maximum removal rate, $\hat{q}$, of 8.35 (mg COD removed)/(mg MLVSS)(day), a half-saturation, K_s, of 94.9 (mg COD)/l and a nonbiodegradable COD of 19.9 mg/l, as shown in Figure 15. The best-fit equation that results is

$$q = \frac{8.35\ (S_{1COD} - 19.9)}{75.0 + (S_{1COD} - 19.9)} \qquad (35)$$

Multiplication of the maximum COD removal rate, $\hat{q}$, by the yield coefficient, Y, produces a maximum specific growth rate of 2.74 day^{-1} based on COD. Although the kinetic constants $\hat{q}$ and $\hat{\mu}$ appear to be slightly on the low side, the values are realistic.

Steady-state measurements and performance parameters based on ATP and dehydrogenase activity also were evaluated with the modified Michaelis-Menten (Monod) equation. The best-fit equations obtained are shown in Figures 16 and 17 and are as follows:

$$q_{ATP} = \frac{43.5\ (S_{1COD} + 6.5)}{949 + (S_{1COD} + 6.5)} \qquad (36)$$

and

$$q_{TF} = \frac{0.584\ (S_{1COD} + 8.9)}{942 + (S_{1COD} + 8.9)} \qquad (37)$$

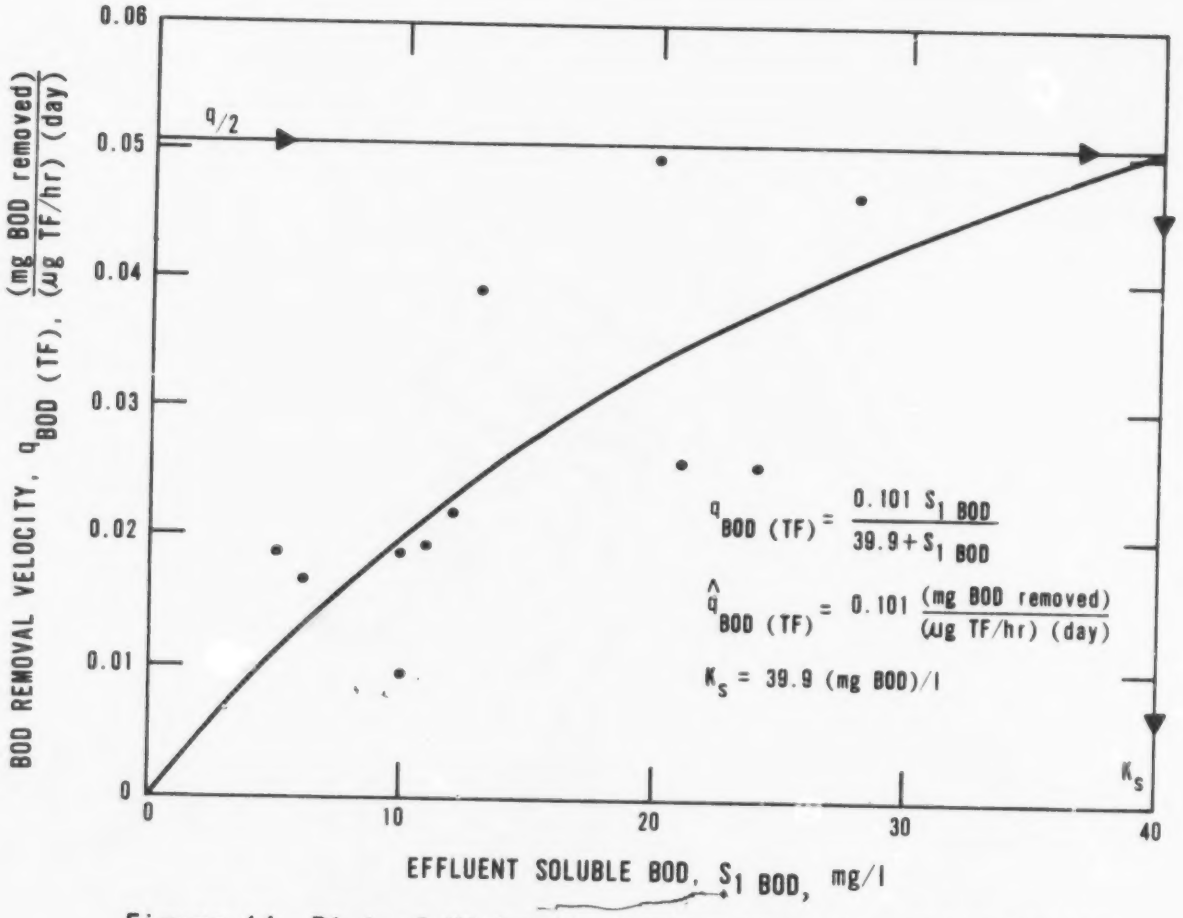


Figure 14 Plot of Michaelis-Menten (Monod) equation using BOD and dehydrogenase activity

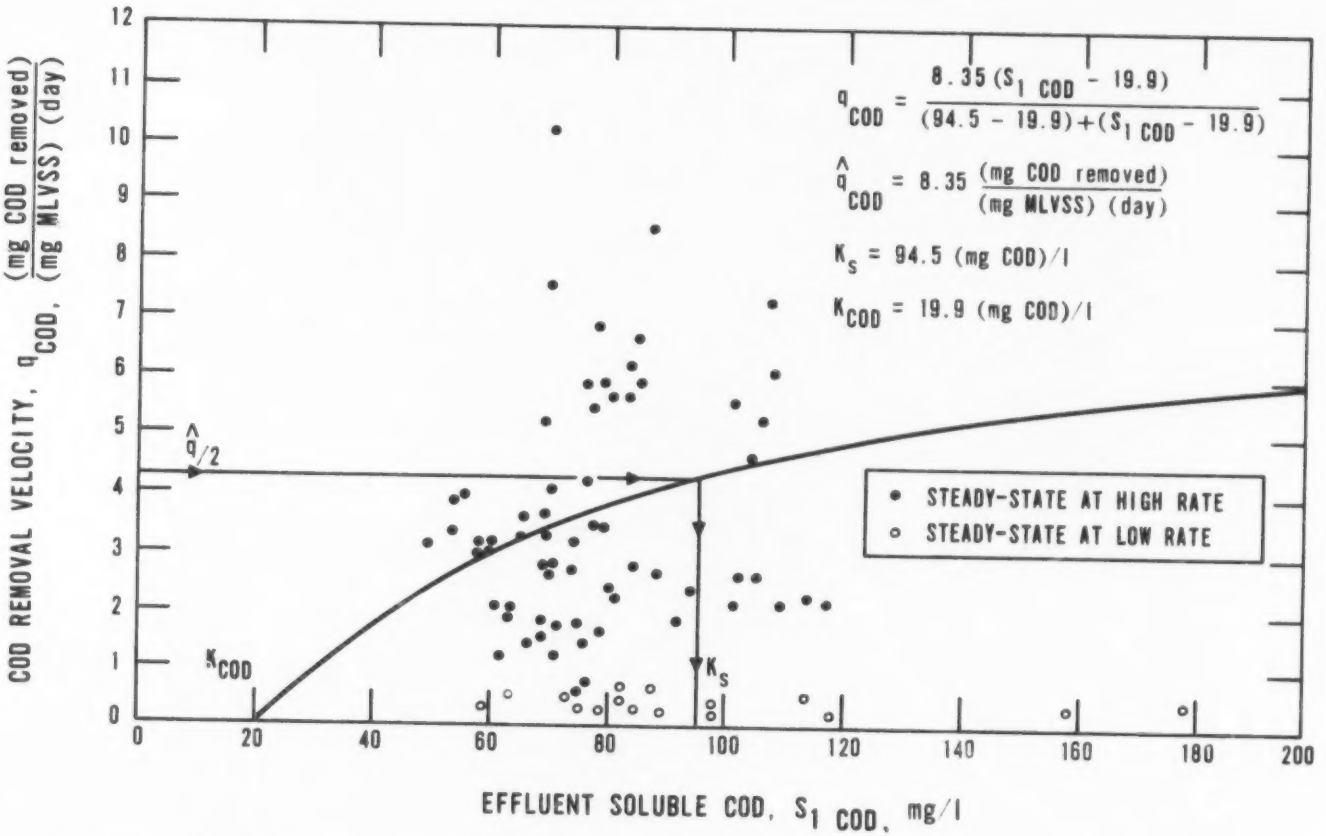


Figure 15 Plot of modified Michaelis-Menten (Monod) equation for accelerated high-rate activated sludge system using COD as substrate parameter

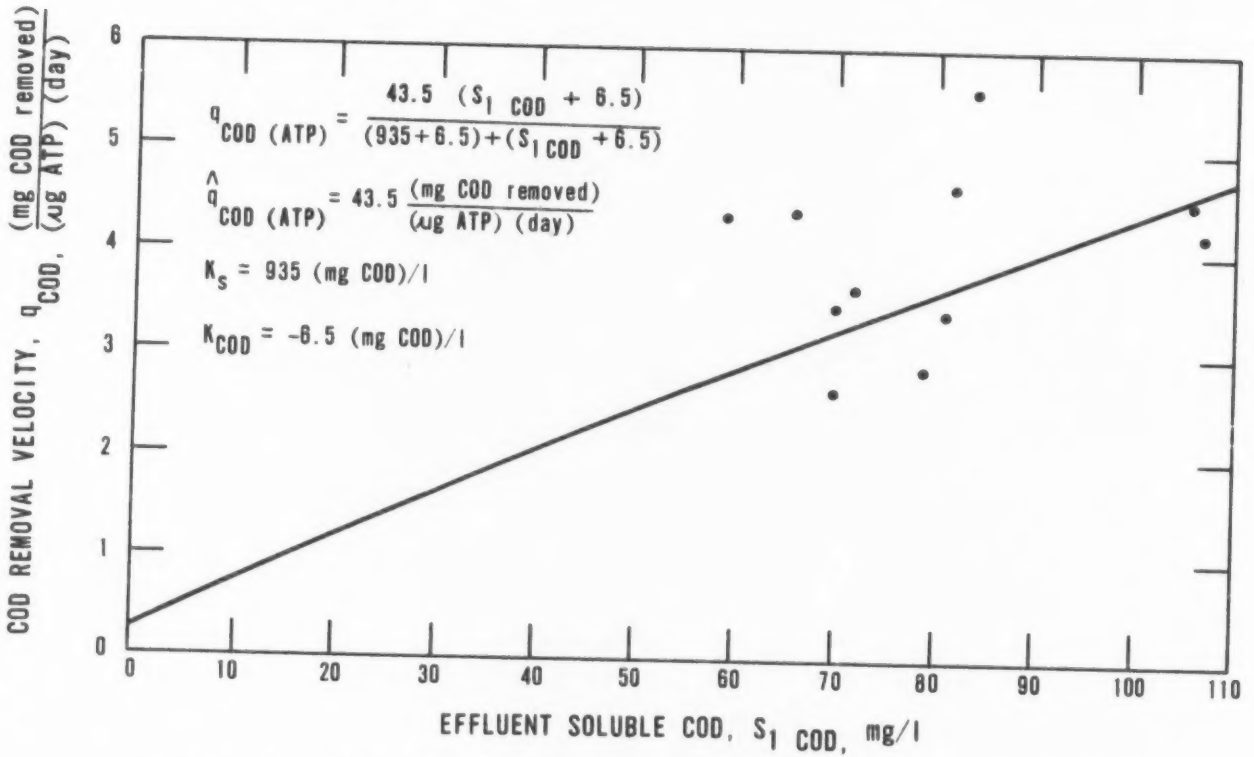


Figure 16 Plot of modified Michaelis–Menten (Monod) equation using COD and ATP

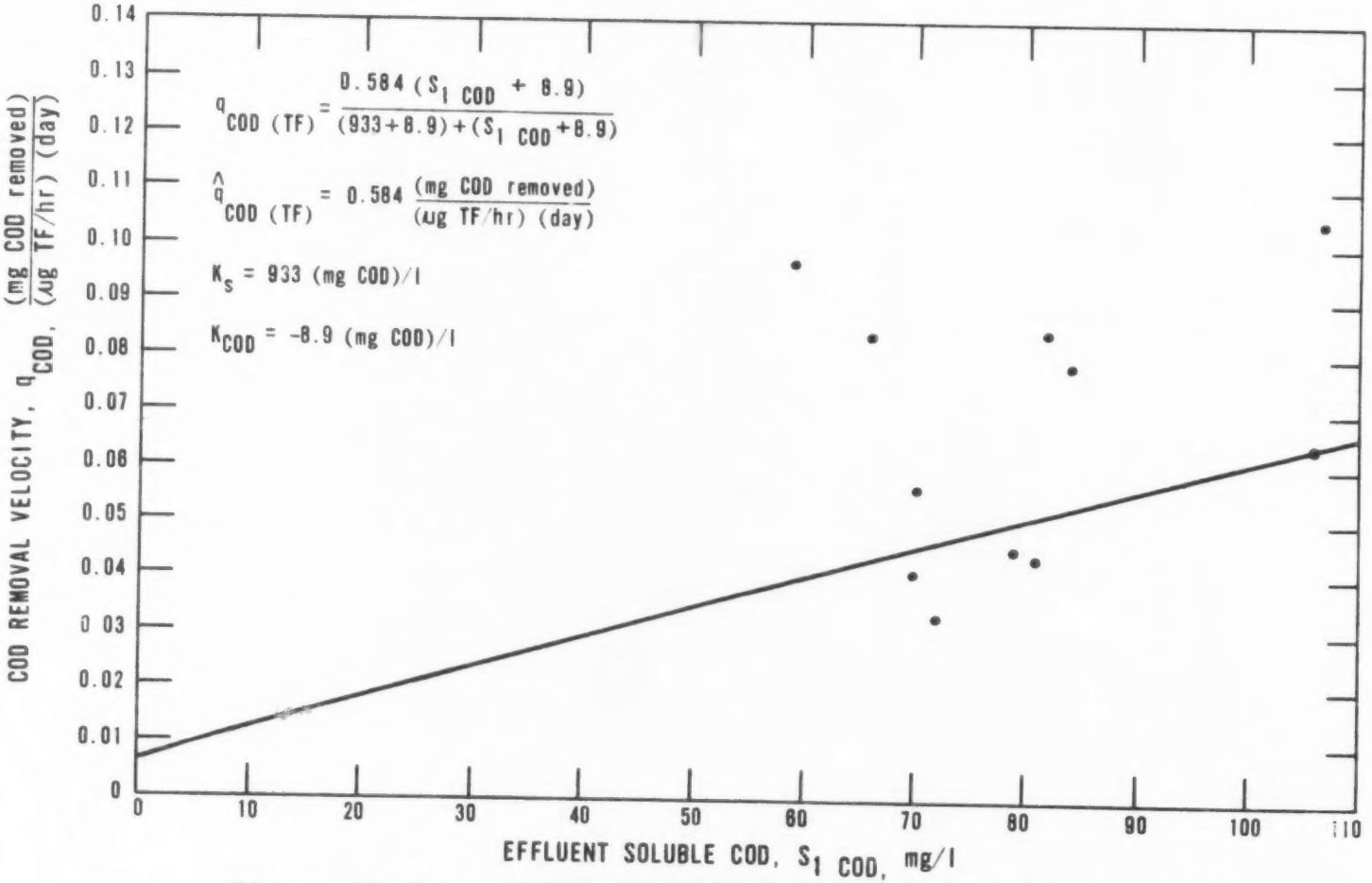


Figure 17 Plot of modified Michaelis-Menten (Monod) equation using COD and dehydrogenase activity

Because of scattered data points (see Figures 16 and 17), both K_s and K_{COD} values, calculated on the basis of ATP and dehydrogenase activity, appear to be unrealistic. Using previously determined ATP and dehydrogenase activity yield coeffieients, *i.e.*, Y_{ATP} = 0.629 (µg ATP produced)/(mg COD removed) and Y_{TF} = 21.0 (µg TF produced/hr)/(mg COD removed), the maximum specific growth rate values were estimated to be unrealistic (27.4 and 12.3 day^{-1} based on ATP and dehydrogenase activity, respectively).

Summary of Accelerated High-Rate Activated Sludge System Kinetic Characteristics

Based upon both theoretical analyses and practical considerations, these studies confirm that one of the most important characteristics of the activated sludge process affecting both performance and operating characteristics is the *active* biological biomass in the system. Thus, it is imperative that accurate estimates of the total active biological biomass in the system be obtained. Three active biomass parameters--MLVSS, ATP and dehydrogenase activity--were considered in the kinetic evaluation of the accelerated high-rate activated sludge system for comparative purposes.

Tables 9 and 10 summarize the kinetic characteristics of the accelerated high-rate activated sludge system based on ATP and dehydrogenase activity as the active biomass measures. Because only 11 steady-state ATP and dehydrogenase activity measurements were obtained during the study period, the kinetic characteristics, obtained from regression analysis, appear to be questionable on a statistical basis.

MLVSS as Active Biomass Parameter--

Reasonable estimates of kinetic constants and kinetic relationships were obtained using MLVSS as the active biomass measure. A summary of the most probable values for the kinetic constants and coefficients Y, k_d, $\hat{q}$, $\hat{\mu}$, K_s and K_{COD} are presented in Table 11. For the purpose of comparison, the reported values of activated sludge process kinetic constants are summarized in Table 12.

Table 9. EVALUATION OF CELL CONTINUITY EQUATION USING ATP AND DEHYDROGENASE ACTIVITY AS ACTIVE BIOMASS PARAMETERS

Active biomass parameters	BOD as substrate parameter		
	Yield coefficient, Y	Decay constant, k_d, day^{-1}	Correlation coefficient, R
ATP	0.661 $\frac{(\mu g \text{ ATP produced})}{(mg \text{ BOD removed})}$	-0.439	0.377
Dehydrogenase activity	24.3 $\frac{(\mu g \text{ TF produced})}{(mg \text{ BOD removed})(hr)}$	-0.834	0.417

COD as substrate parameter		
Yield coefficient, Y	Decay constant, k_d, day^{-1}	Correlation coefficient, R
0.629 $\frac{(\mu g \text{ ATP produced})}{(mg \text{ COD removed})}$	1.045	0.709
21.0 $\frac{(\mu g \text{ TF produced})}{(mg \text{ COD removed})(hr)}$	-0.092	0.678

Table 10. EVALUATION OF MICHAELIS-MENTEN (MONOD) EQUATION USING ATP AND DEHYDROGENASE ACTIVITY AS ACTIVE BIOMASS PARAMETERS

Active biomass parameter	BOD as substrate parameter: Maximum BOD removal velocity, q	BOD as substrate parameter: Half-saturation constant, K_s
ATP	2.30 $\frac{(\text{mg BOD removed})}{(\mu\text{g ATP})(\text{day})}$	5.1 mg/l
Dehydrogenase activity	0.101 $\frac{(\text{mg BOD removed})}{(\mu\text{g TF/hr})(\text{day})}$	29.9 mg/l

COD as substrate parameter: Maximum COD removal velocity, q	COD as substrate parameter: Half-saturation constant, K_s	COD as substrate parameter: Nonbiodegradable COD, K_{COD}
43.5 $\frac{(\text{mg COD removed})}{(\mu\text{g ATP})(\text{day})}$	942 mg/l	- 6.5 mg/l
0.584 $\frac{(\text{mg COD removed})}{(\mu\text{g TF/hr})(\text{day})}$	933 mg/l	- 8.9 mg/l

Table 11. SUMMARY OF MOST PROBABLE KINETIC GROWTH CONSTANTS OF ACCELERATED HIGH-RATE ACTIVATED SLUDGE SYSTEM

Kinetic constants	Substrate parameter	
	BOD	COD
Yield coefficient, Y	0.922 $\frac{(\text{mg MLVSS produced})}{(\text{mg BOD removed})}$	0.328 $\frac{(\text{mg MLVSS produced})}{(\text{mg COD removed})}$
Decay constant, k_d	0.027 day^{-1}	-0.023 day^{-1}
Maximum substrate removal velocity, $\hat{q}$	4.13 $\frac{(\text{mg BOD removed})}{(\text{mg MLVSS})(\text{day})}$	8.35 $\frac{(\text{mg COD removed})}{(\text{mg MLVSS})(\text{day})}$
Maximum specific growth rate, μ	3.81 day^{-1}	2.74 day^{-1}
Half-saturation constant, K_s	26.4 mg/l	94.9 mg/l
Nonbiodegradable substrate concentration, K_{COD}	-	19.9 mg/l

Table 12. ACTIVATED SLUDGE PROCESS KINETIC CONSTANTS

Source	Reference	Substrate	$\hat{q}$, day^{-1}	K_s, mg/l	Y		k_d, day^{-1}
			BOD	BOD	BOD	COD	
Heukelekian	26	Domestic sewage			0.50		0.055
Gram	30	Skim milk	5.1	100	0.48		0.045
Stack	33	Glucose	3.0	355	0.42		0.087
Servici-Bogan	34	Carbohydrates				0.34	
McWhorter-Heukelekian	35	Domestic sewage				0.33	
Eckhoff-Jenkins	23	Synthetic sewage				0.46	0.08
Eckenfelder	12	Pharmaceutical			0.645	0.37	
Dryden	36	Chemical			0.77		0.2
Haas-Pearson	32	Domestic sewage				0.45	0.05
Jenkins-Menar	25	Domestic sewage			0.53	0.33	0.001 - 0.015
Hopwood-Downing	24	Domestic sewage			0.97		
Gram	30	Domestic sewage			0.53		
Jenkins-Garrison	38	Domestic sewage				0.32	0.04
Eckhoff-Jenkins	23	Domestic sewage				0.33	0.05
Middlebrook *et al.*	28	Domestic sewage				0.34	0.016

Yield Coefficient--The yield coefficient, Y, defined as activated sludge produced per unit of substrate removed, was found in this study to be 0.922 (mg MLVSS produced)/(mg BOD removed) and 0.328 (mg MLVSS produced)/(mg COD removed). These yield values are in excellent agreement with yield coefficients reported by many workers (References 22, 23 and 24), *viz.*, 0.50 to 0.97 (mg MLVSS produced)/(mg BOD removed) and 0.32 to 0.46 (mg MLVSS produced)/(mg COD removed). Middlebrooks *et al.*, (Reference 28) has found a yield of 0.34 (mg VSS)/(mg COD) by data analysis of several wastewater treatment installations.

Theoretically, the yield coefficient varies from one organism to another and for the same organism grown on different substrates. The yield values for an activated sludge system represent the overall average yield coefficient of all organisms with respect to the overall substrate and are determined experimentally as a growth constant. However, a varying yield coefficient with specific growth rate has been observed by several workers (References 23 and 29).

Decay Constant--The decay constant, k_d, is a materials balance correction to the specific growth rate, μ, necessitated by endogenous metabolism of cell material, cell death and cell lysis. Many workers have reported the decay rates for activated sludge systems. Heukelekian *et al.* (Reference 26) reported a decay rate of 0.055 day^{-1} on a BOD basis for activated sludge systems based purely on empirical analysis of operating data. Jenkins and Menar (Reference 25) reported k_d values of only 0.001 day^{-1} on a COD basis and 0.015 day^{-1} on a BOD basis. Middlebrooks *et al.* (Reference 28) reported an average decay rate of 0.016 day^{-1} on a BOD basis for several activated sludge installations.

Based on BOD as a substrate measure, a decay of 0.027 day^{-1} was obtained in this study. On the other hand, a negative value of -0.023 day^{-1} was obtained using COD as the substrate measure. There are five possible explanations for a negative decay term: (1) changes in viable fraction of organisms due to changing growth rate, (2) lack of reliable active biomass parameters, (3) error introduced from regression analysis

due to small magnitude of the decay term, (4) varying decay rate as a function of specific growth rate and temperature and (5) analytical error.

Maximum Substrate Removal Velocity and Maximum Specific Growth Rate--The maximum substrate removal velocity, $\hat{q}$, is a growth constant calculated from the Michaelis-Menten (Monod) kinetic model and relates to maximum specific growth rate, $\hat{\mu} = Y\hat{q}$. Very few workers have employed the Michaelis-Menten (Monod) equation in activated sludge kinetic analysis and therefore there are few reported $\hat{q}$ and $\hat{\mu}$ values. Gram's data (Reference 30) permit estimation of a $\hat{q}$ of 3.0 (mg BOD removed)/(mg solids)(day) and Benedek and Horvath (Reference 31) reported a $\hat{q}$ of 5.6 (mg COD removed)/(mg solids)(day).

In this study, the Michaelis-Menten (Monod) equation regression analysis yielded estimates of $\hat{q}$, *viz.*, 4.13 (mg BOD removed)/(mg MLVSS)(day) and 8.35 (mg COD removed)/(mg MLVSS)(day). The corresponding values of maximum specific growth rates were 3.81 and 2.74 day^{-1}, respectively. Theoretically, values of $\hat{\mu}$ calculated on a BOD or COD basis should be identical. The values of $\hat{q}_{COD}$ and $\hat{\mu}_{COD}$ based on COD appear to be slightly below expected values. Comparing the daily steady-state substrate removal velocities (see Table 6) with the corresponding values of $\hat{q}$, it appears that it was possible to operate this activated sludge system at a very high growth rate (note especially Steady-State Periods 7 and 9, Table 6).

Half-Saturation Constant and Nonbiodegradable Substrate Concentration--The half-saturation constant, K_s, is the limiting substrate concentration which can support activated sludge growth at half the maximum growth rate. Again, very limited information is available in the literature on K_s values for activated sludge systems. Pearson and Haas (Reference 32) reported their best estimates of K_s values of 80 (mg BOD)/l and 225 (mg COD)/l for the Whittier Narrows conventional activated sludge plant.

From regression analysis of the Michaelis-Menten (Monod) equation, the K_s in this study were found to be 26.4 (mg BOD)/l and 94.9 (mg COD)/l. Comparison with K_s values reported by Pearson and Haas indicates that the

ratios of K_s values from the two studies based on BOD (0.33) and COD (0.42) are very close. It should be noted that the K_s value is specific for different waste characteristics, different environmental factors and different activated sludge systems. The relatively low values of K_{sBOD} and K_{sCOD} indicate that both BOD and COD are adequate substrate parameters, although BOD appears to be a better parameter than COD. It also appears that the organic substrate concentration expressed as BOD or COD was the rate-limiting factor in the accelerated high-rate activated sludge system.

In the modified Michaelis-Menten (Monod) equation (Equation 34), a certain amount of COD is assumed to be nonbiodegradable in the system. The nonbiodegradable COD concentration is specific for each organism (activated sludge) and wastewater. For the accelerated high-rate system treating the wastewater from the City of Chino, the nonbiodegradable COD concentration is estimated to be about 20 mg/l.

SYSTEM KINETICS WITH OXYGEN TRANSFER

The oxygen transfer requirements of an activated sludge system can be expressed as the sum of oxygen consumption for substrate utilization and the oxygen requirements for sludge oxidation as follows:

$$U = aqX_1 + bk_dX_1 \tag{38}$$

where
- U = rate of oxygen consumption
- a = oxygen requirements per unit substrate removed
- b = oxygen requirements per unit cell oxidized
- q = substrate removal velocity
- k_d = endogenous respiration rate
- X_1 = mixed liquor volatile suspended solids concentration.

To estimate the quantity of oxygen transferred to the mixed liquor by the mechanical aerator, the relationship between oxygen transfer rate and aerator power consumption should be identified. The oxygen transfer

rate is a function of the oxygen transfer coefficient, the power consumption, temperature and the dissolved oxygen concentration gradient at the interface and in the bulk mixed liquor.

During the study period, the dissolved oxygen sensor system was subject to considerable periods of inoperation because of the unavailability of replacement parts; and hence dissolved oxygen concentrations were not measured routinely. The importance of oxygen transfer kinetics in the estimation of oxygen requirements of a balanced design system, as well as in aerator evaluation and selection, however, are recognized. Therefore, to evaluate the oxygen transfer kinetics, the quantity of oxygen transferred to the mixed liquor by the EIMCO-SIMCAR aerator was estimated utilizing the following expression:

$$U = k_t P C_1 C_2 \qquad (39)$$

where U = O_2 transferred/day

P = total kilowatt-hours consumed

C_1 = gear reduction efficiency

C_2 = motor efficiency

k_t = oxygen transfer rate, mass O_2 transferred/power input.

For the EIMCO-SIMCAR aerators, the gear reduction efficiency, C_1, is approximately 0.94; the motor efficiency is approximately 0.92; and the oxygen transfer rate was estimated to be in the range from 0.610 to 2.13 (kg O_2)/(kw-hr consumed) [1.5 to 3.5 (lb O_2)/(hp-hr consumed)] (Reference 39).

Based on several assumed values for the oxygen transfer capacities of the EIMCO-SIMCAR aerators such as 0.92, 1.22, 1.52, 1.83 and 2.13 (kg O_2)/(kw-hr consumed) [1.5, 2.0, 2.5, 3.0 and 3.5 (lb O_2 transferred)/(hp-hr consumed)], the estimated values of the aeration coefficients "a" and "bk_d" are summarized in Table 13. The "a" values ranged from 0.130 to 0.304 (mg O_2)/(mg COD removed) or 0.328 to 0.766 (mg O_2)/(mg BOD removed) and the "bk_d" values ranged from 0.311 to 0.755 (mg O_2)/(mg MLVSS)(day).

Table 13. OXYGEN TRANSFER KINETIC CONSTANTS IN AEROBIC BIOLOGICAL PROCESSES

Substrate	Source	"a"		"bk_d", day^{-1}	
		BOD	COD	BOD	COD
Skim milk	Gram (Reference 30)	0.40	-	0.065	-
Domestic sewage	Downing (Reference 40)	0.50	-	0.100	-
Pulp and paper	Eckenfelder (Reference 12)	0.52	-	0.089	-
Chemical	Dryden (Reference 36)	0.35	-	0.20	-
Kraft pulp	Hazeltine (Reference 37)	0.50	-	0.10	-
	Assumed oxygen transfer rate				
Domestic sewage (this study)	2.13 (kg O_2)/(kw-hr)	0.766	0.304	0.755	0.725
"	1.83 (kg O_2)/(kw-hr)	0.657	0.250	0.647	0.62
"	1.52 (kg O_2)/(kw-hr)	0.548	0.217	0.540	0.518
"	1.22 (kg O_2)/(kw-hr)	0.438	0.174	0.432	0.414
"	0.92 (kg O_2)/(kw-hr)	0.328	0.130	0.324	0.311

Many workers (References 12, 30 and 40) have reported "a" and "bk_d" values on a BOD basis. The typical values obtained for the coefficient "a" range from 0.33 to 0.80 (mg O_2)/(mg BOD) for different synthetic substrates and 0.5 (mg O_2)/(mg BOD) for domestic sewage (Reference 41). Unfortunately, no published information is available for coefficient "a" values based on COD as substrate parameter. Meanwhile, the reported "bk_d" values range from 0.065 to 0.2 (mg O_2)/(mg MLVSS)(day), corresponding to "b" values of 1.0 to 1.44 (mg O_2)/(mg MLVSS).

Comparing the calculated "a" and "bk_d" values with the reported values in Table 13, it appears that "a" and "bk_d" values of 0.438 (mg O_2)/(mg BOD removed) and 0.432 (mg O_2)/(mg MLVSS)(day), respectively, based on an oxygen transfer rate of 1.22 (kg O_2)/(kw-hr consumed) [2.0 (lb O_2)/(hp-hr)] are close to reported values. Table 14 presents the estimated oxygen transfer rates based upon 1.22 (kg O_2)/(kw-hr consumed) [2.0 (lb O_2)/(hp-hr)] transfer rate and substrate (BOD and COD) removal velocities. The amount of oxygen transferred ranged from 0.210 to 1.96 (mg O_2)/(mg MLVSS)(day) and is a linear function of substrate removal velocities, q_{BOD} and q_{COD}, as shown in Figures 18 and 19, respectively.

The "bk_d" values estimated from this study are high compared with values reported in the literature. There are several explanations for the high "bk_d" values: (1) the assumed oxygen transfer coefficient of 0.92 to 2.13 (kg O_2)/(kw-hr) [1.5 to 3.5 (lb O_2)/(hp-hr)] is an oversimplified assumption because the oxygen transfer coefficient is not constant and is a function of aerator type, temperature and oxygen concentration gradient between the interface and in the mixed liquor; (2) the negative value of decay rate, k_d, may influence the ordinate intercept (bk_d) of the oxygen requirements equation (Equation 38); and (3) the decay rate may vary with substrate removal rate or with specific growth rate such that the assumption of a linear relationship between oxygen requirements and substrate removal rate is questionable, especially at low rates.

Table 14. OXYGEN TRANSFER KINETIC DATA AND SLUDGE VOLUME INDEX

Date	Power consumption, kw-hr	Temperature, °C	BOD removal velocity, q, (mg BOD removed)/(mg MLVSS)(day)	COD removal velocity, q, (mg COD removed)/(mg MLVSS)(day)	Oxygen transfer rate, U, (mg O_2)/(mg MLVSS)(day)	Sludge volume index
16Dec70	-	-	0.281	0.347	-	-
17Dec70	-	-	0.278	0.329	-	-
18Dec70	-	-	0.366	0.234	-	-
19Dec70	-	-	0.104	0.249	-	-
20Dec70	-	-	0.176	0.257	-	-
21Dec70	-	-	0.242	0.291	-	-
31Dec70	-	-	0.312	0.367	-	-
2Jan71	678	-	0.173	0.560	0.294	293
3Jan71	654	-	0.172	0.451	0.303	292
5Jan71	677	-	0.184	0.560	0.243	251
15Jan71	794	-	0.253	0.542	0.255	234
16Jan71	567	-	0.296	0.551	0.210	238
17Jan71	670	-	0.268	0.305	0.239	257
18Jan71	719	-	0.314	0.270	0.231	252
15Apr71	489	19.5	0.250	0.619	0.490	87
16Apr71	478	20.0	0.260	0.676	0.590	90
18Apr71	562	18.0	0.206	0.592	0.669	93
19Apr71	384	18.5	0.178	0.783	0.491	169
9May71	432	20.0	0.613	1.20	0.818	189
11May71	460	20.5	0.593	1.49	0.915	226
12May71	477	20.5	0.942	2.04	0.940	227
13May71	459	20.0	0.725	2.26	0.777	229
14May71	475	20.0	0.572	1.90	0.919	176
16May71	441	20.0	0.423	1.28	0.785	207

Table 14 (continued). OXYGEN TRANSFER KINETIC DATA AND SLUDGE VOLUME INDEX

Date	Power consumption, kw-hr	Temperature, °C	BOD removal velocity, q, (mg BOD removed)/(mg MLVSS)(day)	COD removal velocity, q, (mg COD removed)/(mg MLVSS)(day)	Oxygen transfer rate, U, (mg O_2)/(mg MLVSS)(day)	Sludge volume index
16May71	441	20.0	0.423	1.28	0.785	207
17May71	470	20.0	0.485	1.42	0.835	218
18May71	471	20.0	0.504	1.71	0.908	204
19May71	457	20.0	0.449	1.53	0.769	217
20May71	488	20.0	0.567	1.83	0.862	200
21May71	474	20.5	0.693	2,56	0.796	213
23May71	446	20.0	0.754	0.96	0.696	206
24May71	446	21.0	0.718	1.66	0.676	184
25May71	464	21.0	0.812	1.78	0.813	193
28May71	473	20.0	0.519	2.76	0.807	206
29May71	464	20.0	0.625	1.76	0.859	196
16Aug71	372	26.0	1.41	3.42	9.834	72
17Aug71	382	26.0	1.01	2.37	0.748	87
20Aug71	377	25.0	1.25	2.70	0.900	113
23Aug71	380	24.0	1.78	3.63	0.902	124
24Aug71	435	25.0	1.62	3.15	1.22	88
25Aug71	425	24.5	1.73	3.18	1.03	100
26Aug71	433	24.5	1.96	3.20	1.07	121
28Aug71	543	23.0	1.64	3.53	1.21	168
29Aug71	363	24.0	1.29	2.74	0.89	175
30Aug71	448	24.0	1.15	2.60	1.00	138
31Aug71	478	24.0	1.54	5.23	1.11	365

Table 14 (continued). OXYGEN TRANSFER KINETIC DATA AND SLUDGE VOLUME INDEX

Date	Power consumption, kw-hr	Temperature, °C	BOD removal velocity, q, (mg BOD removed)/(mg MLVSS)(day)	COD removal velocity, q, (mg COD removed)/(mg MLVSS)(day)	Oxygen transfer rate, U, (mg O_2)/(mg MLVSS)(day)	Sludge volume index
5Sep71	484	23.0	1.71	3.07	1.03	412
6Sep71	281	23.5	1.50	3.07	0.671	323
9Sep71	374	25.5	1.43	3.37	0.970	171
11Sep71	372	24.0	1.05	3.44	1.09	168
12Sep71	389	25.5	1.73	4.08	1.09	184
13Sep71	398	26.0	1.46	4.20	1.27	199
14Sep71	382	26.0	1.86	3.94	1.02	272
16Sep71	387	25.5	1.78	3.87	9.978	935
17Sep71	375	25.5	1.78	3.08	0.699	549
19Sep71	392	23.5	1.22	3.12	0.928	577
20Sep71	374	24.0	1.30	3.26	0.862	463
28Sep71	365	23.5	3.21	5.96	1.49	581
29Sep71	371	23.0	2.24	5.88	1.35	483
10ct71	400	23.0	2.90	10.2	1.36	434
30ct71	390	22.0	2.50	5.40	1.65	756
40ct71	440	23.0	1.61	5.73	1.85	724
50ct71	395	23.0	2.24	6.64	1.73	826
60ct71	426	23.0	2.08	5.86	1.70	708
70ct71	414	23.5	1.74	6.19	1.57	696
90ct71	383	23.0	2.10	7.52	1.96	283
100ct71	395	23.4	2.06	5.55	1.62	707
110ct71	388	23.5	2.95	7.24	1.76	808

Table 14 (continued). OXYGEN TRANSFER KINETIC DATA AND SLUDGE VOLUME INDEX

Date	Power consumption, kw-hr	Temperature, °C	BOD removal velocity, q, (mg BOD removed)/(mg MLVSS)(day)	COD removal velocity, q, (mg COD removed)/(mg MLVSS)(day)	Oxygen transfer rate, U, (mg O_2)/(mg MLVSS)(day)	Sludge volume index
9Nov71	390	21.0	0.697	2.29	0.511	104
10Nov71	413	21.0	0.762	2.16	0.541	86
14Nov71	388	21.0	0.696	2.14	0.659	422
23Nov71	408	20.0	0.990	2.63	0.843	71
24Nov71	408	20.0	0.815	2.74	0.926	93
25Nov71	408	20.5	0.900	2.34	0.740	110
26Nov71	391	20.0	1.03	2.56	0.821	146
29Nov71	378	21.0	0.778	2.10	0.916	276
2Jan72	381	18.0	2.83	8.57	1.37	-
5Jan72	393	17.0	1.76	5.69	1.77	39
6Jan72	394	17.0	2.34	5.24	1.32	39
8Jan72	379	18.5	1.50	6.06	1.55	25
10Jan72	378	18.0	1.88	4.64	1.69	35
12Jan72	377	18.0	1.78	5.21	1.17	33

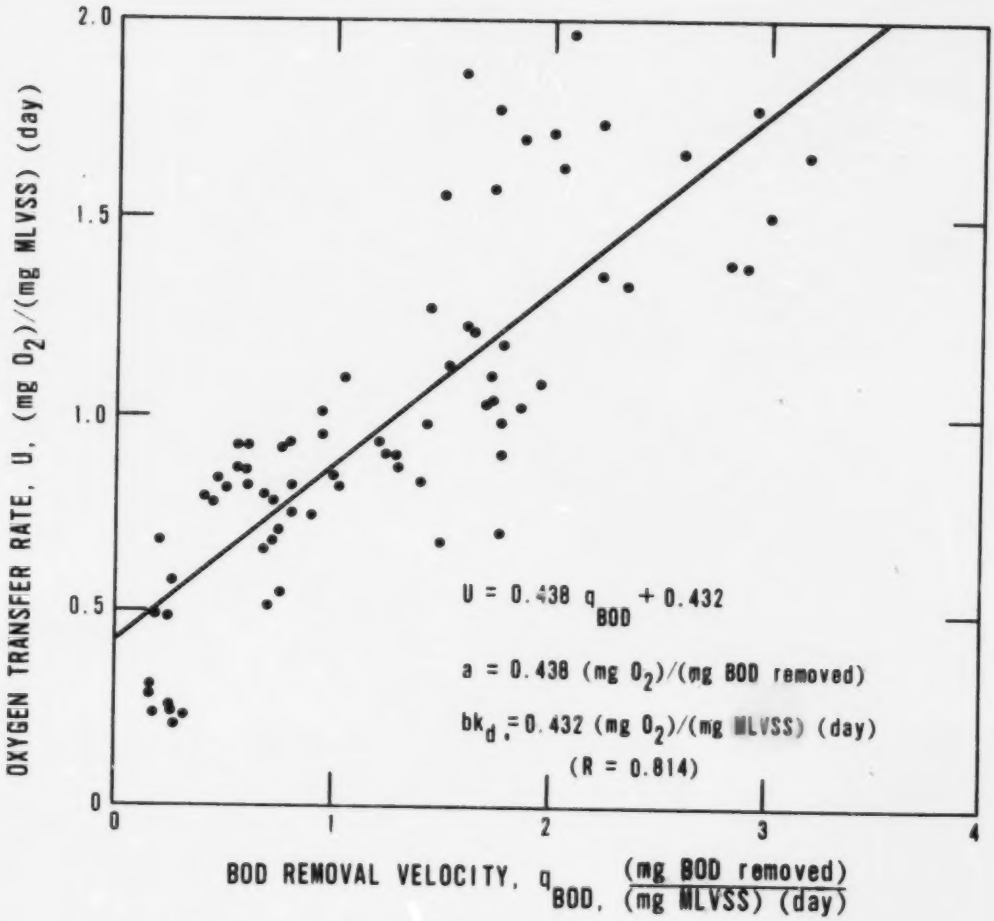


Figure 18 Relationship between oxygen transfer rate and BOD removal velocity

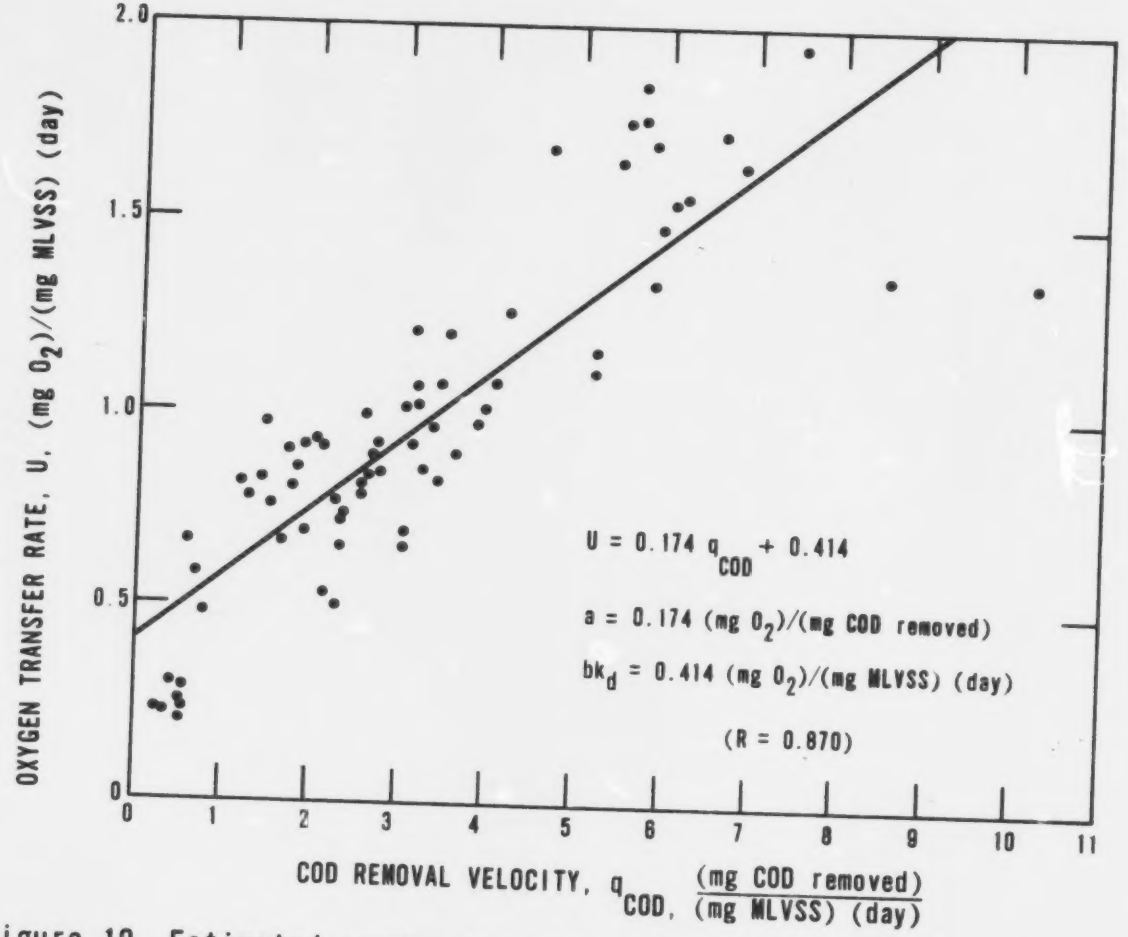


Figure 19 Estimated oxygen transfer rate and COD removal velocity

NUTRIENT REQUIREMENTS AND REMOVAL

In addition to organic substrate (carbon source), organisms require a complex set of nutrients and micronutrients for cellular growth. The principal nutrients required for activated sludge are nitrogen and phosphorus. Therefore, nitrogen and phosphorus requirements, removal efficiencies and removal velocities are of primary concern in activated sludge process analysis.

Table 15 presents data on the total and dissolved nitrogen species (Kjeldahl, ammonia, and nitrite and nitrate) and phosphorus species (total phosphate and orthophosphate) in the primary and secondary effluents.

Nitrogen

The concentrations of various total and dissolved nitrogen species (Kjeldahl, ammonia, and nitrite and nitrate) in the primary and secondary effluents were relatively constant during the 15-month study period, as shown in Table 15. Average total and dissolved nitrogen concentrations in the primary and secondary effluents are summarized in Table 16. Kjeldahl nitrogen represented 99.8 percent or 38.8 mg/l as N of the average total nitrogen content (38.9 mg/l as N) in the primary effluent, and consisted of 59.2 percent ammonia (23.0 mg/l as N) and 40.6 percent organic nitrogen (15.9 mg/l as N). The average dissolved nitrogen fraction in the primary effluent (33.6 mg/l as N) was approximately 86.4 percent of the total in which 86.2 was dissolved Kjeldahl nitrogen, which consisted of 59.2 percent ammonia (23.0 mg/l as N) and 27 percent organic nitrogen (10.6 mg/l as N). Only minor amounts of combined dissolved nitrite and nitrate (0.08 mg/l as N) were present in the primary effluent. In the secondary effluent, average total Kjeldahl nitrogen (29.9 mg/l as N) comprised 97.1 percent of the total nitrogen (30.8 mg/l as N), and average dissolved Kjeldahl nitrogen (27.9 mg/l as N) comprised 90.6 percent of the total nitrogen. Ammonia in the secondary effluent was present totally as dissolved ammonia (20.9 mg/l as N). The average dissolved nitrate and nitrite increased from 0.08 to 0.90 mg/l as N. This indicates that a minor degree of nitrification took place even at the high organic loading velocities and growth rates experienced by the system.

Table 15. STEADY-STATE NITROGEN AND PHOSPHORUS CONCENTRATIONS

Date	Kjeldahl nitrogen, mg/l as N				Ammonia, mg/l as N			Nitrate & nitrite, mg/l as N		Total Phosphate, mg/l as P			
	A	B	C	D	A	C	D	B	D	A	B	C	D
16Dec70	27.1	-	31.0	34.2	23.3	24.2	24.7	0.04	-	11.8		17.8	-
17Dec70	38.1	-	36.2	38.1	21.5	28.1	28.4	0.01	-	10.3	-	20.5	-
18Dec70	44.0	-	38.9	47.3	23.6	29.4	29.4	0.00	-	18.0	-	18.0	15.8
19Dec70	35.3	-	31.8	33.8	21.0	25.0	23.0	0.02	-	15.8	-	14.8	12.8
20Dec70	38.9	-	31.1	31.8	23.3	23.0	23.3	0.25	-	20.0	-	17.0	17.0
21Dec70	37.6	-	30.5	32.4	18.8	--	21.7	0.00	-	21.5	-	13.8	13.3
31Dec70	39.9	-	31.4	30.7	32.2	20.7	22.1	0.00	0.00	20.0	-	16.8	16.0
2Jan71	30.3	-	33.2	30.7	25.7	25.0	24.3	0.00	0.50	23.3	-	17.3	13.3
3Jan71	34.7	-	32.4	31.4	23.7	23.7	24.1	0.00	0.00	16.0	-	16.8	14.8
5Jan71	38.0	-	25.3	28.0	27.6	22.7	23.6	0.00	0.66	15.4	-	18.7	18.2
15Jan71	47.1	-	42.4	33.8	28.6	20.9	22.6	0.00	1.23	18.5	-	36.5	22.5
16Jan71	50.4	-	33.2	31.8	20.9	22.9	23.6	0.00	2.11	19.0	-	19.0	16.5
17Jan71	43.8	-	30.5	28.5	25.6	16.9	17.3	0.00	1.61	27.5	-	21.0	17.0
18Jan71	31.8	-	36.5	31.8	21.6	18.6	17.9	0.30	1.16	24.0	-	22.0	19.0
15Apr71	40.3	-	-	31.5	23.9	23.0	23.3	0.11	0.11	18.8	-	18.8	17.5
16Apr71	41.8	-	-	32.0	-	-	-	-	-	23.0	-	15.5	15.5
18Apr71	37.5	-	-	28.9	24.9	23.1	23.1	0.00	0.00	20.8	-	14.5	12.5
19Apr71	40.0	-	-	28.3	-	-	-	-	-	17.3	-	13.5	13.0
9May71	35.1	-	27.1	25.8	22.2	20.3	20.0	0.00	0.05	10.3	-	--	9.3
11May71	37.5	-	27.7	27.1	-	-	-	-	-	18.8	-	13.8	13.8
12May71	44.3	-	24.6	23.4	-	-	-	--	-	17.8	-	12.5	8.5
13May71	51.7	-	28.9	28.3	23.1	19.1	16.6	0.01	0.04	24.0	-	9.5	7.3
14May71	43.8	-	34.1	31.7	-	-	-	-	-	23.0	-	14.8	14.8
16May71	37.5	-	28.8	27.7	24.0	22.8	22.5	0.01	0.49	18.8	-	15.3	14.3
17May71	38.2	-	29.8	29.6	-	-	-	-	-	21.0	-	21.0	18.8
18May71	40.2	-	28.0	28.0	-	-	-	-	-	21.5	-	15.3	13.8
19May71	40.8	-	30.4	28.6	-	-	-	-	-	22.0	-	14.8	13.8
20May71	40.8	-	29.8	29.8	23.6	21.6	21.6	0.00	0.002	20.0	-	14.3	11.5
21May71	46.3	-	31.7	29.2	-	-	-	-	-	20.0	-	14.5	13.8
23May71	42.0	-	26.8	26.8	23.4	21.3	20.4	-	-	21.0	-	11.5	8.4
24May71	40.2	-	29.8	30.4	-	-	-	-	-	20.0	-	15.8	14.8
25May71	39.6	-	29.8	28.6	-	-	-	-	-	13.3	-	12.0	8.8
28May71	45.7	-	31.7	28.0	-	-	-	-	-	18.8	-	12.8	9.5
29May71	37.7	-	28.6	25.6	-	-	-	-	-	23.0	-	14.8	12.8
16Aug71	38.4	32.8	30.3	22.9	-	-	-	-	-	24.3	22.0	18.8	16.9
17Aug71	35.3	31.6	27.8	23.5	-	-	-	-	-	20.0	20.0	15.3	13.3
20Aug71	37.1	30.9	27.8	24.8	-	-	-	-	-	13.8	11.8	12.3	11.0
23Aug71	36.5	35.3	30.3	24.8	-	-	-	-	-	15.8	15.4	13.0	12.7
24Aug71	35.3	31.5	27.8	23.5	-	-	-	-	-	16.5	15.8	15.1	12.8
25Aug71	38.4	34.7	30.3	22.9	-	-	-	-	-	23.8	23.0	17.3	11.5
26Aug71	37.1	32.2	25.4	21.7	22.8	17.0	17.9	0.04	0.67	19.0	19.0	19.5	14.4
28Aug71	38.9	-	27.2	24.8	-	-	-	-	-	19.3	17.8	11.0	10.9
29Aug71	24.8	24.1	30.3	25.4	21.7	17.0	16.4	0.00	0.84	17.5	16.9	14.8	11.3
30Aug71	34.0	29.1	30.3	26.6	-	-	-	-	-	20.0	20.0	15.1	11.8
31Aug71	45.2	34.0	27.2	26.6	-	-	-	-	-	20.0	20.0	13.3	12.4

[A] Total in primary effluent.

[B] Dissolved in primary effluent.

[C] Total in secondary effluent.

[D] Dissolved in secondary effluent.

Table 15 (continued). STEADY-STATE NITROGEN AND PHOSPHORUS CONCENTRATIONS

Orthophosphate, mg/l as P		Mixed liquor total nitrogen		Mixed liquor total phosphorus,	
B	D	mg/l as N	%	mg/l as P	%
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
9.0	15.5	364	10.6	54.5	1.6
10.0	12.0	309	10.4	18.0	0.61
17.0	11.0	276	9.0	67.5	2.2
16.0	12.5	248	7.3	81.0	2.4
12.0	11.5	430	10.0	120	2.8
-	-	372	10.7	102	2.9
11.8	9.4	374	10.4	161	4.4
-	-	362	10.8	144	4.3
-	-	273	12.0	165	7.3
-	-	247	11.5	80.2	3.7
-	-	271	12.4	186	8.5
-	-	311	12.3	107	4.2
-	-	267	12.0	70.0	3.2
-	-	276	11.4	101	4.2
-	-	280	11.6	88.7	3.7
-	-	255	11.4	95.5	4.3
-	-	284	11.1	105	4.1
12.1	7.6	237	9.7	99.2	4.1
-	-	276	10.8	128	5.0
9.4	6.9	258	9.4	90.2	3.3
-	-	264	9.3	56.2	2.0
-	-	248	10.1	61.0	2.5
-	-	283	11.2	101	4.0
-	-	249	10.7	101	4.3
-	-	241	12.6	53.2	2.8
-	-	277	12.6	122	5.6
-	-	220	12.2	69.7	3.9
-	-	241	13.3	36.1	1.0
-	-	246	16.0	40.5	2.6
-	-	243	13.0	74.5	4.2
10.1	8.6	244	14.1	51.0	2.9
-	-	274	14.2	71.5	3.7
9.1	9.1	215	12.3	130	7.4
-	-	246	12.7	101	5.2
-	-	233	12.7	71.2	3.4

Table 15 (continued). STEADY-STATE NITROGEN AND PHOSPHORUS CONCENTRATIONS

Date	Kjeldahl nitrogen, mg/l as N				Ammonia, mg/l as N			Nitrate & nitrite, mg/l as N		Total phosphate, mg/l as P			
	A	B	C	D	A	C	D	B	D	A	B	C	D
5Sep71	33.1	25.4	23.5	21.6	20.3	16.5	15.9	0.03	0.79	15.3	14.3	8.4	6.8
6Sep71	31.8	30.5	27.3	24.8	-	-	-	-	-	21.0	18.3	17.8	14.4
9Sep71	33.7	30.5	22.2	21.0	-	-	-	0.02	1.41	25.2	21.0	25.2	13.4
11Sep71	33.1	29.2	25.4	22.2	-	-	-	-	-	17.8	17.3	17.8	14.7
12Sep71	36.2	29.2	24.8	20.3	19.4	16.8	17.2	0.35	1.00	15.8	13.8	13.8	11.3
13Sep71	32.4	28.6	27.2	24.2	-	-	-	-	-	15.3	13.8	16.3	16.0
14Sep71	31.1	28.6	22.9	21.6	-	-	-	-	-	15.8	14.8	13.3	13.1
16Sep71	32.4	28.6	25.4	23.5	19.4	16.5	18.4	0.31	0.27	12.0	9.0	11.5	10.8
17Sep71	42.6	38.8	26.7	25.4	-	-	-	-	-	16.8	13.3	12.0	9.5
19Sep71	29.2	26.7	21.6	21.6	18.1	15.9	16.5	0.21	1.22	18.3	18.3	14.3	9.4
20Sep71	30.5	29.9	27.3	24.2	-	-	-	-	-	16.8	16.8	11.3	11.0
28Sep71	36.9	33.1	29.2	24.8	24.8	21.0	21.0	0.00	-	11.3	10.5	13.5	11.3
29Sep71	36.3	24.4	31.2	28.0	-	-	-	-	-	26.5	18.3	23.5	16.8
10Oct71	61.1	41.1	31.8	30.5	-	-	-	-	-	23.0	13.8	11.5	11.5
30Oct71	36.3	33.7	24.2	24.2	22.6	19.7	19.7	0.22	1.44	15.3	12.3	11.3	10.8
4Oct71	35.6	32.5	26.7	21.6	-	-	-	-	-	18.3	14.3	14.3	12.3
5Oct71	35.6	32.5	26.1	25.5	-	-	-	-	-	18.3	15.0	11.0	11.0
6Oct71	36.3	33.7	27.4	27.4	-	-	-	-	-	15.0	15.0	9.0	9.5
7Oct71	39.5	34.4	26.7	26.7	23.9	19.4	19.1	0.32	2.76	14.0	14.0	9.0	8.5
9Oct71	36.3	31.2	31.8	26.7	-	-	-	-	-	16.3	14.0	11.5	11.0
10Oct71	33.7	30.5	24.8	22.9	22.3	17.5	16.2	0.64	4.25	16.3	12.8	12.3	13.8
11Oct71	36.3	31.8	25.5	24.8	-	-	-	-	-	17.3	13.3	12.3	12.8
9Nov71	44.1	39.2	35.9	33.1	-	-	-	-	-	17.3	14.3	12.8	11.5
10Nov71	41.4	38.1	31.4	28.1	-	-	-	-	-	17.3	14.3	13.0	13.0
14Nov71	43.0	35.3	31.6	28.1	24.8	21.0	21.0	0.00	0.65	22.4	20.4	11.3	11.3
23Nov71	39.7	35.9	30.9	28.1	-	-	-	-	-	13.3	12.2	13.5	13.3
24Nov71	38.1	33.6	31.4	27.0	-	-	-	-	-	11.2	11.2	13.3	12.3
25Nov71	43.0	39.2	32.5	28.1	25.1	20.4	20.4	0.00	1.32	16.3	14.3	14.8	11.8
26Nov71	44.4	37.7	35.9	33.5	-	-	-	-	-	13.3	12.2	12.8	13.3
29Nov71	37.7	34.1	31.7	29.8	-	-	-	-	-	15.3	14.3	15.8	13.8
1Jan72	42.3	35.1	31.4	26.0	-	-	-	-	-	14.3	11.2	9.7	9.2
2Jan72	43.5	34.5	33.3	29.0	23.0	19.1	19.1	0.09	0.85	15.3	9.2	11.2	11.8
5Jan72	39.9	35.7	36.3	29.6	-	-	-	-	-	7.1	7.1	8.3	9.2
6Jan72	46.6	40.5	36.9	31.4	25.1	20.6	20.3	0.00	0.48	9.7	6.6	8.2	7.4
8Jan72	41.1	33.3	32.7	29.6	-	-	-	-	-	19.4	15.3	12.2	11.7
10Jan72	41.7	41.7	38.1	32.1	-	-	-	-	-	17.3	10.2	12.2	11.8
12Jan72	49.0	47.8	38.7	36.9	-	-	-	-	-	11.2	11.2	13.8	7.6
Average	38.8	33.5	29.9	27.9	23.0	20.9	20.9	0.08	0.90	17.8	14.8	14.7	12.9

[A] Total in primary effluent.
[B] Dissolved in primary effluent.
[C] Total in secondary effluent.
[D] Dissolved in secondary effluent.

Table 15 (continued). STEADY-STATE NITROGEN AND PHOSPHORUS CONCENTRATIONS

Orthophosphate, mg/l as P		Mixed liquor total nitrogen,		Mixed liquor to phosphorus,	
B	D	mg/l as N	%	mg/l as P	%
12.5	9.1	238	11.8	45.7	2.3
-	-	228	12.7	70.2	3.9
11.8	9.1	294	17.7	89.5	5.4
-	-	232	15.8	81.5	5.5
12.5	7.6	184	12.0	108	7.0
-	-	189	14.0	43.0	3.2
-	-	211	13.1	45.5	2.8
9.4	9.1	216	12.7	53.5	3.2
-	-	283	16.7	49.6	2.9
10.8	9.6	217	11.9	62.3	3.4
-	-	245	13.2	61.8	3.3
-	-	**156**	**14.8**	**30.0**	**2.8**
-	-	**146**	**12.3**	**32.0**	**2.7**
-	-	**190**	**15.1**	**79.5**	**6.3**
13.0	9.1	**134**	**13.3**	**47.0**	**4.6**
-	-	**124**	**12.2**	**50.2**	**4.9**
-	-	**131**	**13.3**	**31.5**	**3.2**
-	-	**146**	**13.6**	**37.0**	**3.4**
10.8	8.4	**154**	**13.6**	**42.2**	**3.7**
-	-	**149**	**17.7**	**28.0**	**3.3**
13.8	11.0	**132**	**12.5**	**41.7**	**4.0**
-	-	**116**	**12.3**	**28.7**	**3.0**
-	-	**333**	**10.2**	**66.4**	**2.0**
-	-	**334**	**10.2**	**59.2**	**1.8**
8.9	9.2	**271**	**10.7**	**57.2**	**2.3**
-	-	**240**	**11.6**	**58.9**	**2.8**
-	-	**240**	**12.6**	**63.4**	**3.3**
7.4	8.9	**275**	**11.6**	**54.1**	**2.8**
-	-	**235**	**11.5**	**51.0**	**2.5**
-	-	**208**	**11.7**	**42.8**	**2.4**
-	-	130	10.9	35.8	3.0
13.3	10.7	119	11.5	33.6	3.1
-	-	123	12.9	22.0	2.3
7.9	5.9	151	11.8	36.8	2.9
-	-	123	11.7	37.7	3.5
-	-	122	12.7	35.2	3.7
-	-	149	10.8	36.8	2.5
11.3	**9.62**		**12.2**		**3.6**

Table 16. AVERAGE NITROGEN AND PHOSPHORUS CONCENTRATIONS IN PRIMARY AND SECONDARY EFFLUENTS

Nutrient	Primary effluent		Secondary effluent	
	Concentration, mg/l as N	Percent, %	Concentration, mg/l as P	Percent, %
Nitrogen				
Total Kjeldahl nitrogen	38.8	99.8	29.9	97.1
Dissolved Kjeldahl nitrogen	33.5	86.2	27.9	90.6
Total ammonia nitrogen	23.0	59.2	20.9	67.9
Dissolved ammonia nitrogen	-	-	20.9	67.9
Dissolved nitrate and nitrite nitrogen	0.08	0.2	0.90	2.9
Total dissolved nitrogen	33.58	86.4	28.80	93.5
Total nitrogen	38.88	100.	30.8	100
Phosphorus				
Dissolved orthophosphate	11.3	63.5	9.62	65.4
Total dissolved phosphate	14.8	83.2	12.9	87.7
Total phosphate	17.8	100	14.7	100

Nitrogen removal by the activated sludge process is accomplished by the synthesis of nitrogen in the activated sludge and possibly by denitrification. It is assumed that both the dissolved and particulate nitrogenous forms in the primary effluent are available for biosynthesis. Because most solids in the secondary effluent are biological cells, excess nutrients are assumed to be present only in soluble forms.

Table 17 presents the nitrogen removal efficiencies and removal velocities of various nitrogen species. Removal efficiencies for the various nitrogen species were relatively constant when the system was operated at high rates. However, the removal efficiencies varied widely when the system was operated at low rates, *i.e.*, $1/\theta_c = 0.036$ to $0.071\ \text{day}^{-1}$. Approximately 27 percent of the total Kjeldahl nitrogen and 22 percent of the dissolved Kjeldahl nitrogen was removed by activated sludge. Based on grab sample measurements during a three-day period, only 8.2 percent of the ammonia present was incorporated into cell material. It appears that the nitrogen supply in the primary effluent was in gross excess of that required for activated sludge growth; hence, nitrogen was not the limiting nutrient in this study.

The net yield coefficient with respect to specific nutrient can be defined as the net amount of cells produced per unit amount of nutrient removed, or

$$Y_n = \frac{\text{cells produced}}{\text{nutrient removed}} = \frac{FX_2 + F_w(X_r - X_2)}{F(S_0 - S_1)} \tag{40}$$

or

$$Y_n = \frac{1}{\theta_c q}$$

where

$$\theta_c = \frac{VX_1}{FX_2 + F_w(X_r - X_2)} \tag{18}$$

$$q = \frac{F(S_0 - S_1)}{VX_1} \tag{15}$$

Table 17. NUTRIENT REMOVAL VELOCITIES AND REMOVAL EFFICIENCIES

Date	Nutrient removal velocity, $\frac{(mg\ N\ or\ P\ removed)}{(mg\ MLVSS)(day)}$					
	Total Kjeldahl nitrogen	Dissolved Kjeldahl nitrogen	Ammonia nitrogen	Total phosphate	Total dissolved phosphate	Dissolved ortho-phosphate
16Dec70	-0.0173	-	-0.0034	-	-	-
17Dec70	0.	-	-0.0141	-	-	-
18Dec70	-0.0064	-	-0.0114	0.0043	-	-
19Dec70	0.0024	-	-0.0032	0.0048	-	-
20Dec70	0.0110	-	0.	0.0046	-	-
21Dec70	0.0084	-	-0.0047	0.0295	-	-
31Dec70	0.0198	-	0.0025	0.0092	-	-
2Jan71	-0.0007	-	0.0025	0.0183	-	-
3Jan71	0.0064	-	-0.0007	0.0023	-	-
5Jan71	0.0150	-	0.0060	-0.0042	-	-
15Jan71	0.0225	-	0.0101	-0.0067	-	-0.0110
16Jan71	0.0364	-	-0.0070	0.0049	-	-0.0039
17Jan71	0.0286	-	0.0155	0.0196	-	0.0112
18Jan71	0.	-	0.0062	0.0084	-	0.0059
15Apr71	0.0.86	-	0.0012	0.0027	-	0.0011
16Apr71	0.0240	-	-	0.0183	-	-
18Apr71	-0.0230	-	0.0048	0.0222	-	0.0064
19Apr71	0.0336	-	-	0.0123	-	-
9May71	0.0559	-	0.0132	0.0060	-	-
11May71	0.0629	-	-	0.0302	-	-
12May71	-0.125	-	-	0.0058	-	-
13May71	0.124	-	0.0343	0.0803	-	-
14May71	0.0712	-	-	0.0483	-	-
16May71	0.0531	-	0.0081	0.0243	-	-
17May71	0.0490	-	-	0.0124	-	-
18May71	0.0715	-	-	0.0451	-	-
19May71	0.0652	-	-	0.0438	-	-
20May71	0.0617	-	0.0100	0.0476	-	0.0252
21May71	0.0911	-	-	0.0330	-	-
23May71	0.0753	-	0.0148	0.0624	-	0.0124
24May71	0.0472	-	-	0.0250	-	-
25May71	0.0612	-	-	0.0250	-	-
28May71	0.0998	-	-	0.0524	-	-
29May71	0.0741	-	-	0.0625	-	-
16Aug71	0.202	0.129	-	0.0965	0.0660	-
17Aug71	0.134	0.0921	-	0.0760	0.0761	-
20Aug71	0.162	0.0805	-	0.0369	0.0105	-
23Aug71	0.157	0.141	-	0.0415	0.0362	-
24Aug71	0.180	0.124	-	0.0566	0.0459	-
25Aug71	0.218	0.166	-	0.173	0.162	-
26Aug71	0.222	0.151	0.0705	0.0662	0.0663	0.0216
28Aug71	0.195	-	-	0.116	0.0952	-
29Aug71	-0.0087	-0.0247	0.0775	0.0906	0.106	0.
30Aug71	0.0933	0.0315	-	0.103	0.1036	-
31Aug71	0.253	0.101	-	0.104	0.1036	-

Table 17 (continued). NUTRIENT REMOVAL VELOCITIES AND REMOVAL EFFICIENCIES

Nutrient removal efficiency, %					
Total Kjeldahl nitrogen	Dissolved Kjeldahl nitrogen	Ammonia nitrogen	Total phosphate	Total dissolved phosphate	Dissolved ortho-phosphate
-26	-	-6.0	-	-	-
0	-	-32	-	-	-
-7.5	-	-25	12	-	-
4.2	-	-9.5	19	-	-
2	-	0	15	-	-
14	-	15	58	-	-
22	-	4.7	20	-	-
-1.3	-	5.4	43	-	-
9.5	-	-1.7	7.5	-	-
26	-	14	-18	-	-
28	-	21	-22	-	-72
37	-	-18	13	-	-20
35	-	32	38	-	35
0	-	17	21	-	22
22	-	2.5	- 6.9	-	4.2
23	-	-	33	-	-
23	-	7.2	40	-	20
29	-	-	25	-	-
26	-	9.9	9.7	-	-
28	-	-	26	-	-
47	-	-	52	-	-
45	-	28	70	-	-
28	-	-	35	-	-
26	-	6.2	24	-	-
23	-	-	10	-	-
30	-	-	36	-	-
29	-	-	37	-	-
27	-	7.7	42	-	37
37	-	-	31	-	-
36	-	13	60	-	27
24	-	-	26	-	-
28	-	-	34	-	-
39	-	-	49	-	-
32	-	-	44	-	-
40	30	-	30	23	-
33	26	-	34	34	-
33	20	-	20	6.8	-
32	30	-	20	18	-
33	26	-	22	19	-
40	34	-	52	50	-
42	32	21	24	24	15
36	-	-	44	39	-
2.4	5.4	24	35	33	0.
22	8.6	-	41	41	-
41	22	-	38	38	-

Table 17 (continued). NUTRIENT REMOVAL VELOCITIES AND REMOVAL EFFICIENCIES

Date	Nutrient removal velocity, $\frac{(mg\ N\ or\ P\ removed)}{(mg\ MLVSS)(day)}$					
	Total Kjeldahl nitrogen	Dissolved Kjeldahl nitrogen	Ammonia nitrogen	Total phosphate	Total dissolved phosphate	Dissolved ortho-phosphate
5Sep71	0.144	0.0475	0.0549	0.106	0.0939	0.0425
6Sep71	0.0921	0.0752	-	0.0869	0.0514	-
9Sep71	0.189	0.141	-	0.175	0.1129	0.0401
11Sep71	0.188	0.121	-	0.0533	0.0448	-
12Sep71	0.252	0.142	0.0349	0.0713	0.0397	0.0770
13Sep71	0.149	0.0800	-	-0.0127	-0.0400	-
14Sep71	0.145	0.107	-	0.0412	0.0260	-
16Sep71	0.131	0.0750	0.0146	0.0176	-0.0264	0.0044
17Sep71	0.254	0.199	-	0.108	0.0563	-
19Sep71	0.104	0.0699	0.0281	0.122	0.122	0.0165
20Sep71	0.0831	0.0752	-	0.0765	0.0766	-
28Sep71	0.288	0.198	-	0.	-0.0190	-
29Sep71	0.163	0.123	-	0.205	0.0317	-
10Oct71	0.623	0.218	-	0.230	0.0461	-
30Oct71	0.286	0.224	0.0684	0.106	0.0354	0.0921
4Oct71	0.341	0.266	-	0.146	0.0487	-
5Oct71	0.240	0.167	-	0.174	0.0945	-
6Oct71	0.199	0.141	-	0.123	0.123	-
7Oct71	0.268	0.161	0.100	0.115	0.115	0.0503
9Oct71	0.276	0.129	-	0.152	0.0862	-
10Oct71	0.244	0.172	0.138	0.0566	-0.0226	0.0634
11Oct71	0.290	0.177	-	0.114	0.0126	-
9Nov71	0.0861	0.0478	-	0.0454	0.0219	-
10Nov71	0.106	0.0796	-	0.0341	0.0103	-
14Nov71	0.148	0.0716	0.0377	0.110	0.0906	-0.0030
23Nov71	0.131	0.0884	-	0.	-0.0124	-
24Nov71	0.139	0.0828	-	-0.0138	-0.0138	-
25Nov71	0.147	0.110	-	0.0444	0.0247	-0.0149
26Nov71	0.126	0.0485	-	0.	-0.0127	-
29Nov71	0.106	0.0577	-	0.0201	0.0067	-
1Jan72	0.346	0.194	-	0.108	0.0425	-
2Jan72	0.348	0.132	0.0935	0.0839	-0.0625	0.0625

Table 17 (continued). NUTRIENT REMOVAL VELOCITIES AND REMOVAL EFFICIENCIES

Nutrient removal efficiency, %					
Total Kjeldahl nitrogen	Dissolved Kjeldahl nitrogen	Ammonia nitrogen	Total phosphate	Total dissolved phosphate	Dissolved ortho-phosphate
35	15	22	56	52	27
22	19	-	31	21	-
38	31	-	47	36	23
33	24	-	17	15	-
44	30	11	28	18	39
25	15	-	-4.6	-16	-
30	24	-	17	11	-
27	18	5.1	10	-20	3.2
40	34	-	[illegible]	28	-
26	19	8.8	49	49	11
21	19	-	34	34	-
33	25	-	0	-7.6	-
21	17	-	37	8.2	-
50	26	-	50	17	-
33	28	13	39	12	30
39	33	-	33	14	-
28	22	-	40	27	-
24	19	-	37	37	-
32	22	20	39	39	22
26	14	-	32	21	-
32	25	27	15	-7.8	20
32	22	-	26	3.8	-
25	16	-	34	20	-
32	26	-	25	9.1	-
35	20	15	50	45	3.4
29	22	-	0	-9.0	-
29	20	-	-9.8	-9.8	-
35	28	19	28	17	-20
24	11	-	0	9.0	-
21	13	-	8.8	3.5	-
38	26	-	36	18	-
33	16	17	23	-28	20

Based on these net growth expressions, the net yield coefficients of various nitrogen species were computed to be as follows:

$$Y_n = 11.3 \frac{\text{(mg MLVSS produced)}}{\text{(mg Kjeldahl nitrogen removed)}}$$

$$Y_n = 20.1 \frac{\text{(mg MLVSS produced)}}{\text{(mg total ammonia nitrogen removed)}}$$

Because no nitrogen analyses were made directly on the cells, the nitrogen content in the activated sludge was estimated from the difference between total particulate and dissolved nitrogen concentrations determined on the mixed liquor. The calculated total nitrogen concentrations in the activated sludge are listed in Table 15. The concentrations varied between 7.3 and 16.8 percent, with an average of 12.2 percent. This average nitrogen content of activated sludge corresponds to a nitrogen yield coefficient of 8.21 (mg MLVSS produced)/(mg total nitrogen removed). These yield values and nitrogen content appear to be realistic estimates of the nitrogen conversion and are within the range of reported values which vary from 5.6 to 12.4 percent (References 28, 42, 43 and 44).

Phosphorus

Daily steady-state total phosphate and total dissolved phosphate measurements were made on the primary and secondary effluents. Dissolved orthophosphate was determined on three-day grab samples of the primary and secondary effluents. These results are presented in Table 15. Total phosphate expressed as P in the primary effluent varied from 7.1 to 26.5 with an average of 17.8 mg/l as P and the total dissolved phosphate ranged from 7.1 to 23, with an average of 14.8 mg/l. On the other hand, the total dissolved phosphate in the secondary effluent varied from 6.8 to 22.5, with an average of 12.9 mg/l, and the total phosphate varied from 8.2 to 36.5, with an average of 14.7 mg/l as P. From three-day grab sample analyses, dissolved orthophosphate expressed as P varied from 7.4 to 17.0, with an average of 11.3 mg/l, in the primary effluent; and 5.9 to 15.5, with an average of 9.62 mg/l, in the secondary effluent.

Table 17 also presents the phosphate removal efficiencies and removal velocities which were calculated based on the assumptions that both the particulate and dissolved phosphate in the primary effluent are available for biosynthesis and excess phosphates are present in the soluble forms in the secondary effluent. Approximately 27.8 percent of total phosphate or 16.1 percent of total dissolved phosphate was removed by activated sludge. Based on three-day grab sample analyses, 12 percent of dissolved orthophosphate was incorporated into cell material. It appears that phosphorus supply in the primary effluent was in gross excess of the phosphorus required for cellular growth; hence phosphorus was not the limiting nutrient in this study.

The net yield coefficients (Equation 40) based on phosphorus were found to be as follows:

$$Y_n = 14.4 \frac{\text{(mg MLVSS produced)}}{\text{(mg total dissolved phosphate as P removed)}}$$

$$Y_n = 28.5 \frac{\text{(mg MLVSS produced)}}{\text{(mg dissolved orthophosphate as P removed)}}$$

Since no phosphorus analyses were made on activated sludge, the phosphorus content in the activated sludge was estimated from the difference between total particulate and dissolved phosphorus concentration made on the mixed liquor. The estimated phosphorus contents in the activated sludge varied from 0.61 to 7.39 percent with an average of 3.60 percent (Table 15). This average phosphorus content of activated sludge corresponds to a phosphorus yield coefficient of 27.8 (mg MLVSS produced)/(mg phosphorus removed).

Reported values of phosphorus content in activated sludge range from 2 to 3 percent (Reference 25). The slightly high phosphorus content of cells noted in this study may have been caused by greater phosphate uptake rate and greater phosphorus storage. Excess phosphate uptake was observed by Tocrien *et al.* (Reference 7) in an algal growth kinetic study under phosphorus limitation using *Selenastrum capricornutum* as a test organism.

In the treatment of several nutrient-deficient industrial wastes, Helmers *et al.* (Reference 45) determined minimal quantities of nitrogen and phosphorus of 40 (mg N)/(g BOD removed) and 6 (mg P)/(g BOD removed). This is approximately equivalent to a BOD:N:P ratio of 150:5:1. Because the BOD:N:P ratio was 150:48:22 in the primary effluent, it is obvious that neither nitrogen nor phosphorus was a limiting nutrient in this process. Although in the absence of typical values of half-saturation constants of nitrogen and phosphorus (K_{sN} and K_{sP}), it is conceivable that the nitrogen and phosphorus concentrations in the aeration tank and effluent (S_{1N} or S_{1P}) were much greater than the K_{sN} or K_{sP} values; that is, $S_{1N} >> K_{sN}$ and $S_{1P} >> K_{sP}$. Thus, the nitrogen and phosphorus removal velocities (q_N or q_P) were zero-order with respect to S_{1N} or S_{1P}. Consequently, the Michaelis-Menten (Monod) model (Equation 3) for nitrogen or phosphorus as a limiting nutrient is not applicable. Furthermore, since other macronutrients and micronutrients are usually present in sufficient quantity in domestic sewage, the organic substrate measured as BOD or COD appeared to be the sole growth limiting factor in this study.

SOLIDS SEPARATION

The activated sludge process incorporates soluble and particulate materials into a mass of biological solids which must be separated from the process effluent. Sludge settling and compacting characteristics are a primary requisite to successful operation of the activated sludge process. One of the objectives of this study was the evaluation of selected alternative solids separation systems. The selected systems included vibratory screening, enhanced gravity sedimentation, dissolved air flotation and pressurized hydro-centrifugal screening.

Sludge Settling Characteristics

Several sludge characteristics are of importance in determining sludge settleability. These sludge characteristics are particle size distribution, particle shape, particle density, particle surface charge and sludge volume index. The project was too limited to continuously monitor all of these

sludge characteristics and correlate them with sludge settleability and activated sludge operating parameters. However, some qualitative analyses can be summarized.

Sludge volume index measurements were made on mixed liquor under presumed steady-state conditions and are presented in Table 14. Sludge volume index varied from 25 at an organic loading rate of 2.00 (mg BOD)/(mg MLVSS)(day) to 935 at an organic loading rate of 1.94 (mg BOD)/(mg MLVSS)(day). Figure 20 shows the variations of sludge volume index with BOD loading and COD loading rates. No apparent relationships can be developed from these widely scattered data.

It was observed that at low organic loading rate, *e.g.*, less than 1.0 (mg BOD)/(mg MLVSS)(day) or 3.0 (mg COD)/(mg MLVSS)(day), the colloidal materials in the primary effluent were effectively flocculated by activated sludge. At higher organic loadings, the flocculating capacity of the activated sludge apparently was insufficient to flocculate all colloidal particles causing a very turbid secondary effluent.

Qualitative morphological microscopic examinations revealed that the percentage of filamentous organisms present in activated sludge increased with increased sludge volume index; also increases in organic loading tended to stimulate the growth of filamentous organisms.

Vibratory Screening

A set of SWECO vibrating screens, equipped with three interchangeable screen materials, was incorporated into the facility. The three screens supplied with the units included 0.044- and 0.037-mm opening (325- and 400-mesh) stainless steel plain weave screens, and a 0.014- by 0.105-mm opening (720- by 140-mesh) dutch twilled stainless steel screen. Each screen was equipped with a fine spray washing system for removal of trapped materials.

The screens were tested under varying operating conditions which included screen size opening, speed of vibratory motor, solids and hydraulic loading rates and the angle between top and bottom vibratory

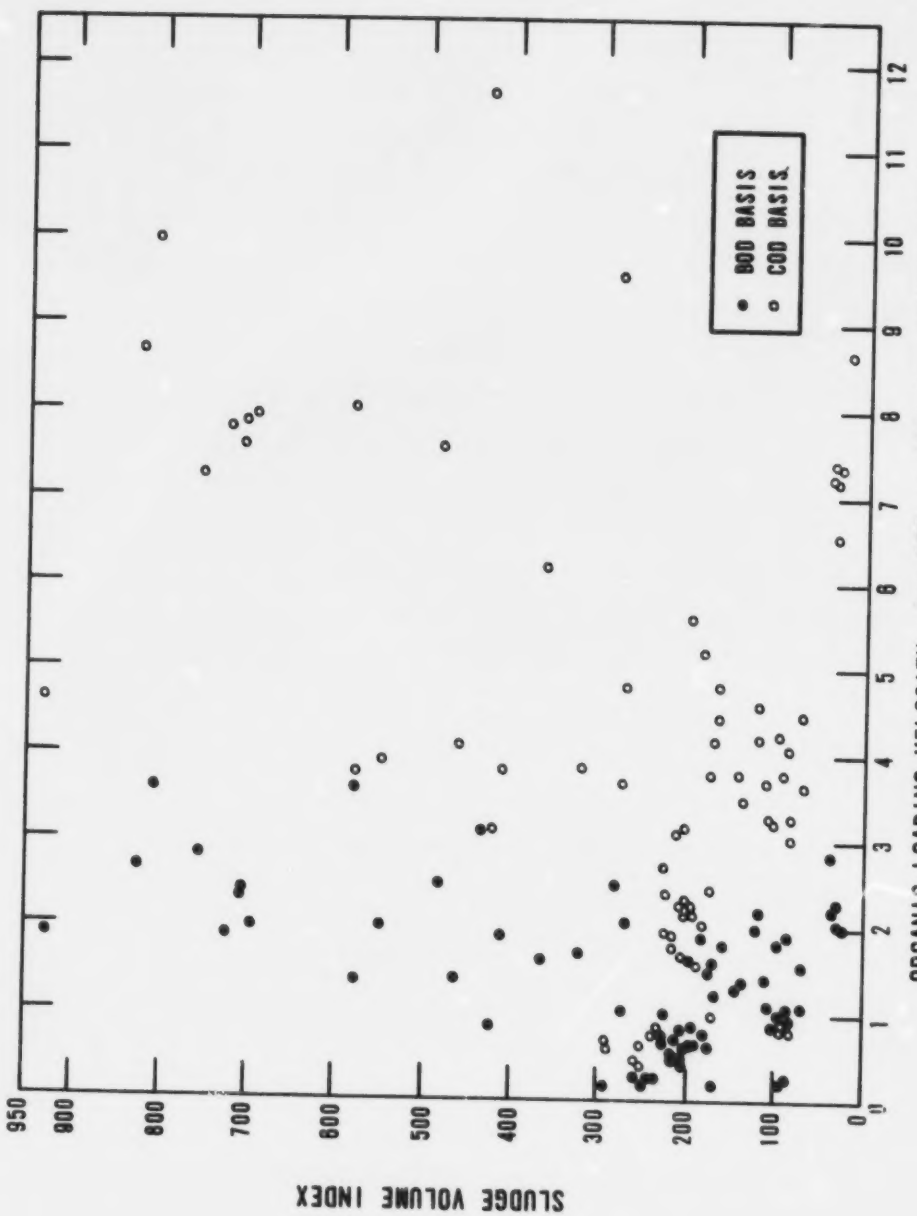


Figure 20 Effect of organic loading velocity on sludge volume index

weights. Table 18 presents the screen performance characteristics and operating conditions. Average values of solids removal efficiencies and filtration rates are summarized in Table 19. The speed of the vibratory motor, in the narrow range of 1,100 to 1,500 rpm, and the angle between vibratory weights were not found to have a significant effect on performance and were discounted from further consideration.

Average solids removal efficiencies from the effluent stream with the 0.044- and 0.037-mm opening (325- and 400-mesh) screens were 38 and 49 percent, at average filtration rates of 16.6 and 16.0 $m^3/(m^2)(day)$ [408 and 393 $gal/(ft^2)(day)$], respectively, which are considered to be unacceptable performance. Suspended solids recovery with these screens was too low to return sufficient solids to the aeration tank. Average solids removal efficiencies with the 0.014- by 0.105-mm opening (720- by 140-mesh) screen averaged 91 percent (a value approaching the performance of gravity settlers) at an average filtration rate of 2.98 $m^3/(m^2)(day)$ [73.2 $gal/(ft^2)(day)$].

Hydraulic capacities of the vibratory screens are presented in Figures 21, 22 and 23. Normalized filtration rates, which are the ratio of filtration rate to hydraulic loading rates were plotted against the corresponding solids loading rates for each screen size. The hydraulic capacity of the 0.044-mm opening (325-mesh) screen depicted in Figure 21 appears to be nearly independent of solids loading rate.

Normalized filtration rates of the 0.037-mm opening (400-mesh) screen generally decreases as solids loading rates increased, as shown in Figure 22. Results were erratic, but this smaller mesh size was apparently more susceptible to hydraulic head losses caused by suspended solids and hydraulic loading than the 0.044-mm opening (325-mesh) screen.

Whereas the solids removal efficiency of the 0.014- by 0.105-mm opening (720- by 140-mesh) screen was acceptable, the filtration rate was far from acceptable at the suspended solids concentrations applied. At solids loading rates on the order of 97.9 $kg/(m^2)(day)$ [20.0 $lb/(ft^2)(day)$], generally less than 10 percent of the applied hydraulic flow passed through the filters, as shown in Figure 23.

Table 18. VIBRATORY SCREEN PERFORMANCE DATA

Test Number	Solids loading rate, kg/(m²)(day)	Filtration rate, m³/(m²)(day)	Filtration rate/ hydraulic loading ratio	Influent suspended solids, mg/l	Effluent suspended solids, mg/l	Solids removal efficiency, %	Screen opening, μ
1	34.2	12.9	0.84	2230	1310	41.3	44
2	24.7	10.0	0.91	2230	1200	46.2	44
3	33.0	6.88	0.62	3000	1160	61.3	44
4	20.5	8.75	0.89	2100	1410	32.8	44
5	28.4	12.0	0.88	2100	1400	33.3	44
6	14.8	6.63	0.94	2100	1310	37.6	44
7	17.5	7.65	0.92	2100	1180	44.0	44
8	117	29.3	0.72	2880	1610	44.1	44
9	132	40.7	0.89	2880	1670	42.0	44
10	89.7	27.6	0.88	2880	1390	51.7	44
11	108	33.9	0.90	2880	1480	48.8	44
12	79.8	18.6	0.77	3340	1880	43.6	44
13	30.2	8.02	0.89	3340	1860	44.5	44
14	59.7	12.5	0.69	3340	1720	48.5	44
15	30.2	8.14	0.90	3340	1620	51.6	44
16	71.3	15.9	0.77	3440	1850	46.2	44
17	50.2	12.1	0.83	3440	1780	48.2	44
18	111	22.2	0.69	3440	1680	51.0	44
19	93.2	24.1	0.89	3440	1690	50.9	44
20	76.4	17.1	0.78	3460	1620	53.0	44
21	50.9	10.7	0.73	3460	1900	45.0	44
22	109	22.1	0.70	3460	1940	43.8	44
23	61.7	14.8	0.82	3450	1800	47.7	44
24	38.0	8.18	0.74	3450	2510	27.3	44
25	46.6	12.0	0.88	3450	1890	45.2	44
26	41.1	9.32	0.79	3500	1860	49.8	44
27	47.3	11.3	0.83	3500	2160	38.3	44
28	68.4	16.6	0.85	3500	1980	43.4	44
29	83.6	20.7	0.86	3500	1870	46.5	44
30	54.1	12.3	0.84	3720	2100	43.7	44
31	43.7	9.69	0.82	3720	2160	42.0	44
32	56.8	12.0	0.79	3720	2160	42.0	44
33	28.5	7.00	0.91	3710	2790	24.7	44
34	33.5	7.00	0.77	3710	2760	25.5	44
35	54.0	13.5	0.92	3710	3240	12.5	44
36	26.9	6.15	0.80	3500	1700	51.4	44
37	31.7	8.38	0.93	3500	2290	34.6	44
38	41.1	10.6	0.90	3500	2080	40.6	44
39	64.2	12.9	0.66	3290	1740	47.3	44
40	29.7	8.22	0.91	3290	1840	44.0	44
41	18.1	4.40	0.80	3290	1430	56.5	44
42	148	25.1	0.51	3010	1990	33.9	44
43	35.3	11.0	0.94	3010	1910	36.5	44
44	155	38.9	0.74	2960	1920	35.0	44
45	36.9	11.7	0.94	2960	1980	33.0	44

Table 18 (continued). VIBRATORY SCREEN PERFORMANCE DATA

Test Number	Solids loading rate, kg/(m²)(day)	Filtration rate, m³/(m²)(day)	Filtration rate/ hydraulic loading ratio	Influent suspended solids, mg/l	Effluent suspended solids, mg/l	Solids removal efficiency, %	Screen opening, -
46	193	39.9	0.73	3540	2420	31.6	44
47	206	55.4	0.95	3540	2920	17.5	44
48	52.6	13.0	0.85	3440	2480	27.9	44
49	55.0	13.7	0.85	3440	1680	51.2	44
50	105	23.6	0.91	4050	3500	13.6	44
51	109	23.9	0.88	4050	2770	31.6	44
52	114	25.8	0.92	4050	3110	23.2	44
53	106	24.2	0.93	4070	3200	21.2	44
54	76.2	18.1	0.97	4070	3170	22.1	44
55	88.8	19.7	0.90	4070	2830	30.5	44
56	76.8	17.6	0.90	3930	2550	35.1	44
57	81.4	21.0	0.96	3730	3100	17.0	44
58	53.9	14.4	0.94	3530	2990	15.3	44
59	53.5	14.0	0.96	3680	1790	51.4	44
60	88.0	20.5	0.86	3680	2620	28.8	44
61	51.0	12.3	0.91	3780	2440	35.5	44
62	98.2	24.4	0.94	3780	2550	32.5	44
63	70.4	16.4	0.91	3720	2350	36.9	44
64	104	25.8	0.93	3720	2140	32.7	44
65	58.6	16.0	0.90	3320	2160	38.1	44
66	92.4	26.2	0.94	3520	2100	40.5	44
67	61.7	13.4	0.65	3490	2150	38.4	44
68	97.2	26.3	0.94	3490	2660	23.7	44
69	76.1	15.8	0.84	4070	2760	32.1	44
70	121	27.9	0.94	4070	3100	23.8	44
71	30.2	8.06	0.59	2230	860	61.4	37
72	25.0	5.70	0.68	3000	830	72.3	37
73	19.0	7.77	0.86	2100	1040	50.2	37
74	104	27.0	0.75	2880	1180	59.0	37
75	120	10.6	0.29	3340	1640	50.7	37
76	131	17.1	0.45	3460	1840	46.6	37
77	115	28.7	0.86	3450	1950	43.5	37
78	98.2	10.6	0.37	3500	2030	42.0	37
79	118	28.4	0.72	3010	2320	22.8	37
80	62.8	7.98	0.36	2880	1400	51.6	14 x 105
81	37.9	9.73	0.88	2440	330	90.4	14 x 105
82	36.6	2.08	0.23	4050	300	92.6	14 x 105
83	93.0	1.42	0.06	4070	180	95.6	14 x 105
84	81.3	0.24	0.01	3930	130	96.7	14 x 105
85	105	3.79	0.13	3730	160	95.7	14 x 105
86	67.5	0.41	0.02	3780	90	97.6	14 x 105
87	86.4	2.24	0.09	3780	100	97.4	14 x 105
88	93.0	0.98	0.04	4070	168	95.9	14 x 105
89	101	0.81	0.03	4070	130	96.8	14 x 105

Table 19. SUMMARY OF VIBRATORY SCREEN PERFORMANCE

Screen Mesh Number	Opening, μ	Average influent solids concentration, mg/l	Average solids removal efficiency, %	Average filtration rate, $m^3/(m^2)(day)$
325	44	3,395	38.0	17.3
400	37	2,997	49.0	16.0
720 x 140	14 x 105	3,780	91.0	2.97

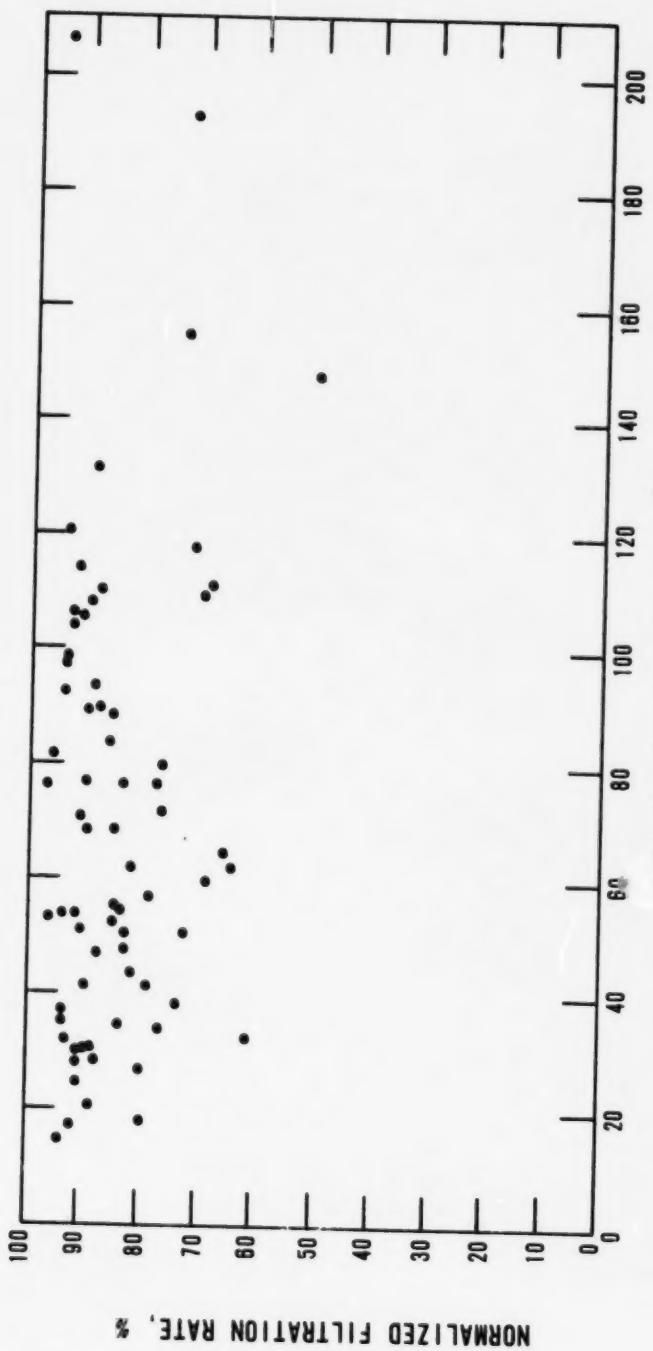


Figure 21 Hydraulic capacity of vibratory 0.044-mm opening (325-mesh) screen

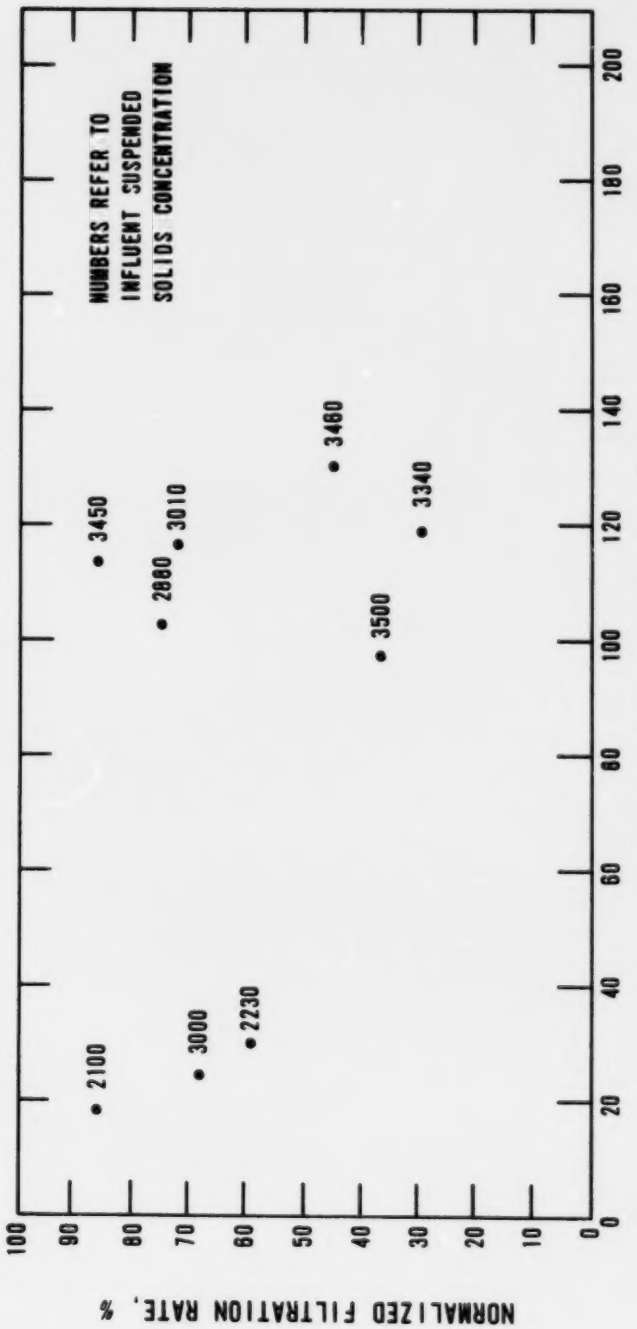


Figure 22 Hydraulic capacity of vibratory 0.037-mm opening (400-mesh) screen

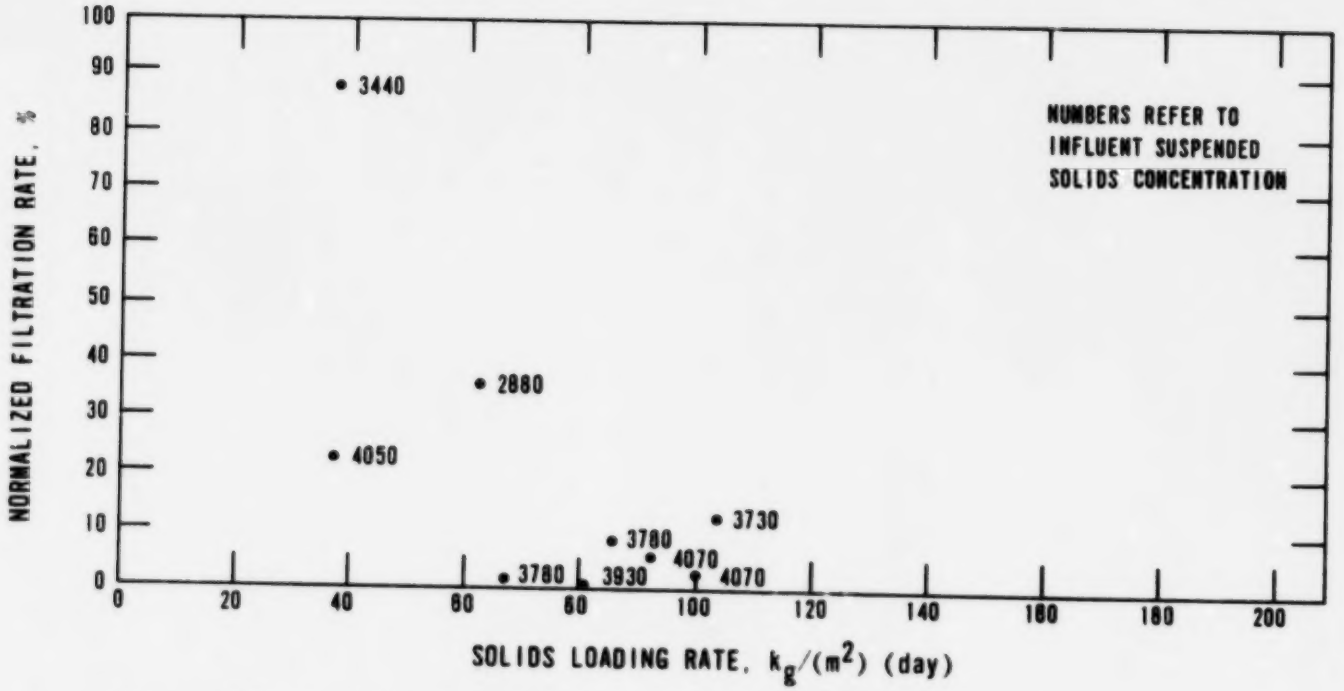


Figure 23 Hydraulic capacity of vibratory 0.014- by 0.105-mm opening (720- by 140-mesh) screen

Because the attainment of relatively high filtration rates could not be achieved with the type of vibratory screening provided for this study, the testing of the vibratory screens was discontinued in favor of enhanced gravity sedimentation.

Enhanced Gravity Separation

During the studies of the accelerated high-rate activated sludge system, suspended solids removal from the mixed liquor was accomplished by two circular, 16.8-m (55-ft) diameter gravity settlers. Both settlers were operated in parallel during each steady-state period and their performance was determined from analyses drawn from a common effluent sump and a common return solids sump. Table 20 summarizes average operating parameters and performance characteristics of the gravity settlers during the steady-state activated sludge process operations.

The effect of hydraulic surface loading rate on gravity settler performance is shown in Figure 24. The hydraulic surface loading rate varied between 5.0 and 13.3 $m^3/(m^2)(day)$ [123 and 327 $gal/(ft^2)(day)$] in the tests at Chino. These surface loading rates are much lower than those usually used, *i.e.*, about 32.6 $m^3/(m^2)(day)$ [800 $gal/(ft^2)(day)$] for conventional activated sludge processes. With the exception of the single high value point, effluent suspended solids appeared to be little affected by hydraulic surface loading rates in the range studied. Although return sludge solids concentrations generally decreased with increasing hydraulic surface loading rates, the large variations of concentrations encountered in the extremely narrow range of surface loading rates between 12.2 and 13.4 $m^3/(m^2)(day)$ [300 and 330 $gal/(ft^2)(day)$] indicate the influence of a factor other than surface loading rate.

The effect of mean cell age on gravity settler performance is shown in Figure 25. Return solids concentration from the gravity settlers indicated a marked increase with increasing mean cell age. The five widely spread return solids concentrations, indicated in Figure 24 in the narrow range of hydraulic loading rates, 12.3 and 13.4 $m^3/(m^2)(day)$ [300 and 330 $gal/(ft^2)(day)$], achieve greater significance in their apparently closer relationship to mean cell age. Effluent suspended

Table 20. GRAVITY SETTLER PERFORMANCE

Steady-state run	Surface loading rate, $m^3/(m^2)(day)$	Solids loading rate, $kg/(m^2)(day)$	Mean cell age, day	Suspended Solids mg/l		Return sludge solids, mg/l
				Influent	Effluent	
1	9.89	33.2	32.4	3,370	38	6,270
2	12.3	47.4	16.6	3,860	47	9,600
3	5.01	23.0	3.17	4,610	29	8,770
4	7.20	20.5	1.58	2,850	26	7,250
5	7.45	24.0	1.39	3.180	40	8,100
6	13.1	28.4	0.737	2,180	31	5,070
7	13.0	18.1	0.525	1,380	25	3,560
8	13.3	37.7	1.57	2,810	38	7,060
9	12.6	17.6	0.446	1,390	71	3,590

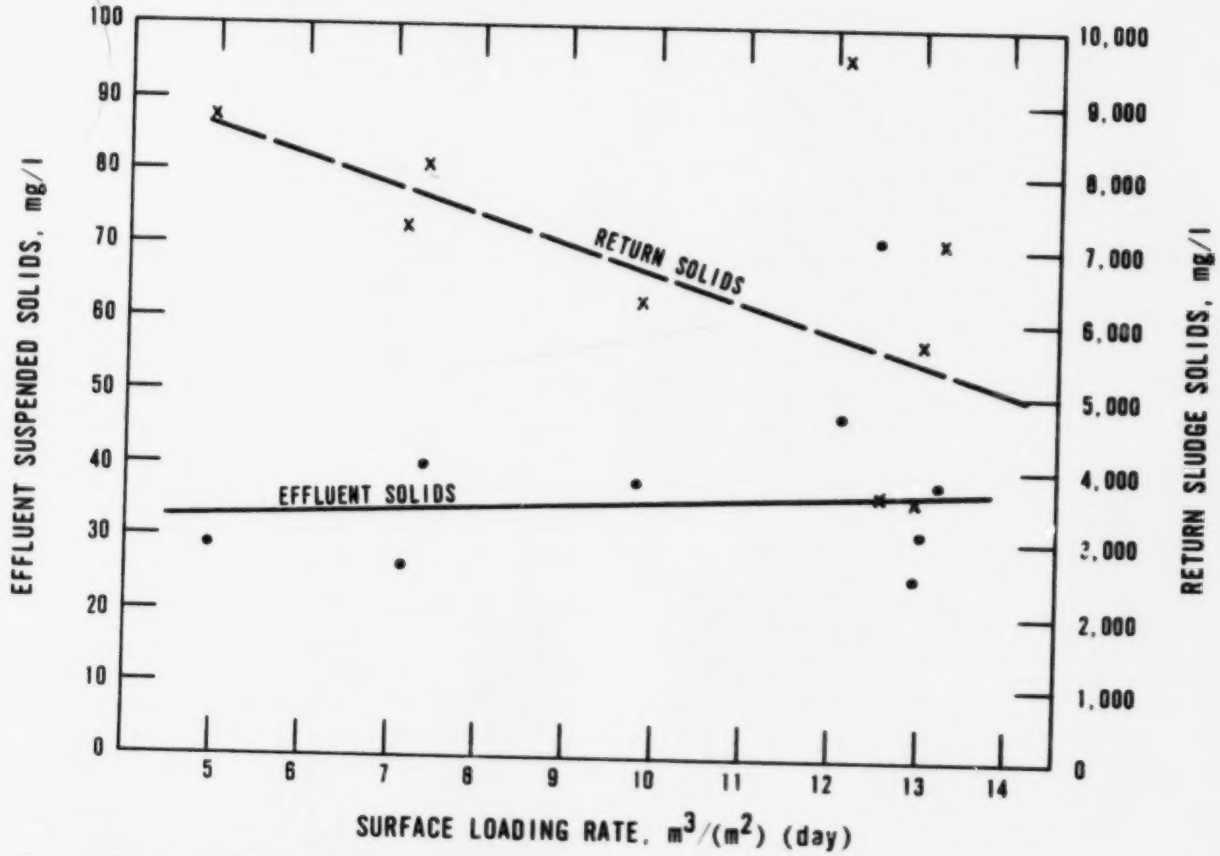


Figure 24 Effect of surface loading on gravity settler performance

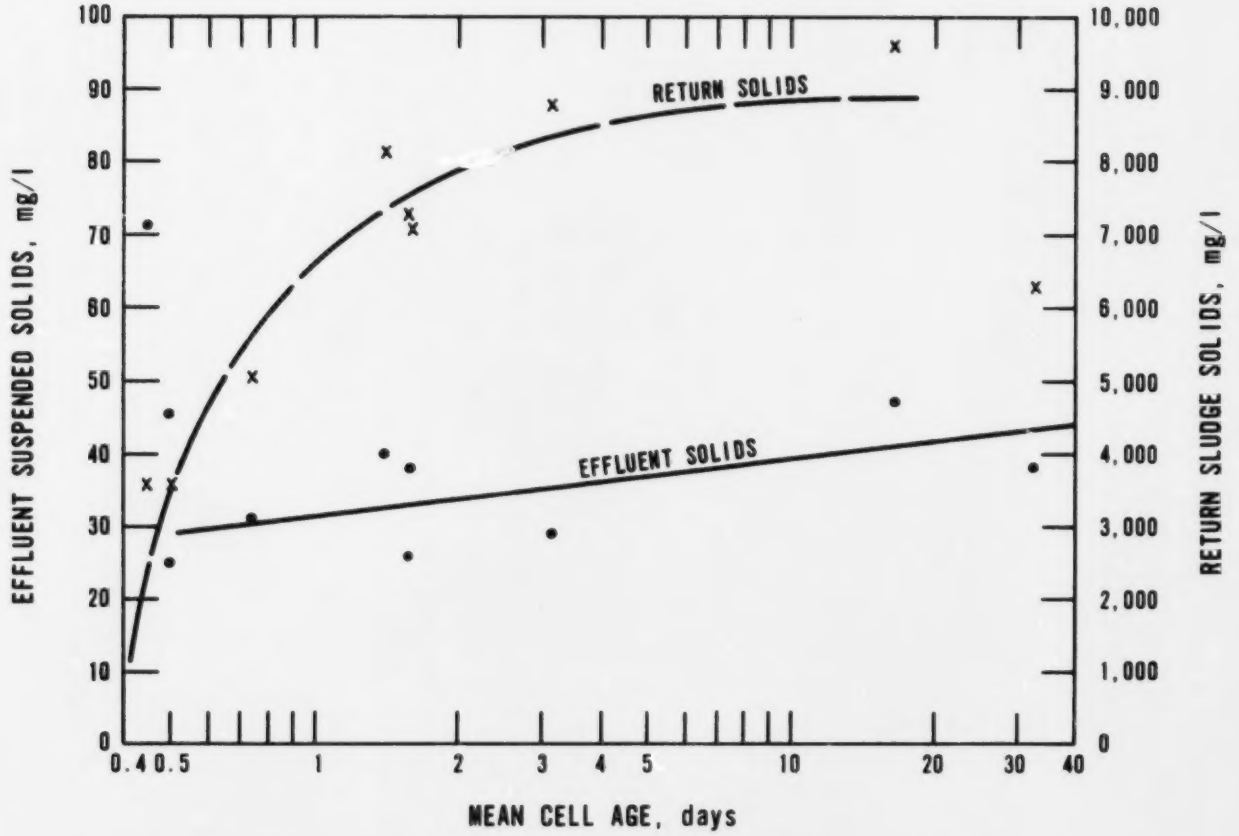


Figure 25 Effect of cell age on gravity settler performance

solids concentrations, on the other hand, indicated only a very slight increase from 30 to 40 mg/l with increasing sludge age. It would appear, therefore, that it is possible to achieve acceptable effluent solids concentrations with a gravity settler over a very wide, *i.e.*, two orders of magnitude, range of mean cell ages.

To get an indication of the potential advantage of slowly stirring the settling sludge to effect a greater sludge compaction, one gravity settler was equipped with 6.35-cm (2.5-in.) vertical angle pickets spaced 38.1 cm (15 in.) apart on the traveling suction arm and extended to within 61 cm (24 in.) of the water surface. Both settlers were then operated with identical feeds and feed rates during Steady-State Runs 3 through 9. The sludge blanket in the picket-equipped gravity settler was observed to be 30 to 61 cm (12 to 24 in.) lower than in the other settler. A common sludge sump for the two settlers prevented ready analytical verification of the improved compaction.

Pressurized Hydro-Centrifugal Screens

It is believed that vibratory screening could be successfully used as an activated sludge separation system if a continuous cleaning of screen surface and a pressure mechanism were provided. Consequently, a greater practical filtration rate and higher solids removal rate could be achieved. A device consisting of a screen mounted on discs which can be spun in a pressure vessel appears to have potential as a mechanical solids separation system for the high-rate activated sludge process.

A small wastewater concentrator was loaned from SWECO for evaluation. The screening surface is mounted on a vertical spinning circular cage with the feed distributed from the inside toward the screen. As the liquid passes through the screen from the centrifugal force, the solids are transported down the screen by gravity and collected separately. A cleaning cycle is also built into the unit to eliminate grease binding.

Unfortunately, within the scope of this project, this concept and unit could not be tested or evaluated; however, the need for research is indicated.

Dissolved Air Flotation

Dissolved air flotation was selected as an alternative separation system because it provides larger compactive forces for concentrating separated materials as compared to conventional gravity clarification.

The pilot flotator leased from EIMCO was 1.53 m (5 ft) in diameter and was equipped with a float skimming system, bottom rakes and a draw-off for settled solids. The unit was also equipped with EIMCO's standard two-stage pressurization system for dissolving air in a recycle stream drawn from the effluent of the unit. The hydraulic loading of this flotator was between 20.3 and 122 $m^3/(m^2)(day)$ [500 and 3,000 $gal/(ft^2)(day)$] with relatively good suspended solids capture. If a coagulant aid and polymer were added properly, the solids in the effluent were well flocculated and could be easily removed by granular media filtration.

One test run was made on the pilot flotator which was operated at approximately 81.4 $m^3/(m^2)(day)$ [2,000 $gal/(ft^2)(day)$] with 20 percent effluent recycle. The ferric chloride dose used was approximately 150 mg/l, the polymer was 1.0 mg/l of Calgon Catfloc and the pH of the recycle stream was 8.3.

The effluent suspended solids concentration was 22 mg/l with a volatile portion of 5 mg/l. The low magnitude of volatile suspended solids would indicate that the solids were ferric chloride flocs rather than activated sludge solids. It appears that the flotation system could be effective in separating activated sludge. Moreover, it is expected that a considerable amount of phosphate compounds could be removed.

This air flotation solid separation program was only designed to indicate its general feasibility and potential in activated sludge separation application. Complete system evaluation of dissolved air flotation is indicated.

SECTION VIII

DESIGN AND OPERATIONAL IMPLICATIONS

The design and operation of domestic waste treatment plants have evolved largely from practical experience with full-scale systems. Theoretical analysis has been directed largely to explaining the phenomena observed in practice. To date such analysis has not been fully applied to either design or operation of real systems. Such a dilemma results from the interaction of several pertinent considerations. One of the major factors has been the lack of adequate theoretical bases for analysis of the process. A second, and possibly more important, factor has been the poor communication between the theoretician concerned primarily with the theory and performance criteria of the process and the practitioner who is concerned largely with compliance with traditional treatment concepts and effluent quality or performance criteria established by regulatory agencies.

Complete kinetic description of the activated sludge process that has been derived from actual plant data would permit evaluation of the theoretical model and would make possible more accurate predictions of process performance as well as indicate opportunities for improved process design and operation. One of the great advantages of using a rational kinetic model to describe the activated sludge process is that it considers both the microbial kinetic characteristics, which are a function of the complex biological system operative, as well as the effect of physical factors such as the hydraulic residence time, cellular recycle, oxygen transfer rates and the cellular residence time. These latter factors are affected by the intentional sludge wasting rate, the settleability of the mixed liquor and the effectiveness of the solids separation system.

KINETIC DESCRIPTION OF ACCELERATED HIGH-RATE ACTIVATED SLUDGE SYSTEM

The results from this study have yielded a kinetic description of the accelerated high-rate activated sludge system and what appear to be reasonable values for the kinetic constants and coefficients which can be utilized in the analysis and design of waste treatment systems, especially for high-rate activated sludge systems.

The kinetic analyses suggest that the net growth rate of activated sludge, $1/\theta_c$, in a high-rate process is a linear function of the substrate removal velocity, q, and a constant endogenous respiration rate, k_d, or

$$1/\theta_c = Yq - k_d$$

In terms of BOD as the rate-limiting substance,

$$1/\theta_c = 0.922\ q_{BOD} - 0.027$$

and in terms of COD as the rate-limiting substance,

$$1/\theta_c = 0.328\ q_{COD} + 0.023$$

The kinetic analysis also suggests that the organic substrate concentration, expressed as BOD or biodegradable COD, was the growth limiting factor in the system and the Micahaelis-Menten (Monod) model can be successfully employed to describe the substrate removal velocity and substrate concentration relationship, *viz.*,

$$q = \frac{\hat{q}S_1}{K_S + S_1}$$

or

$$q_{BOD} = \frac{4.1\ S_{1BOD}}{26 + S_{1BOD}}$$

and $$q_{COD} = \frac{8.4\ (S_{1COD} - 20)}{75 + (S_{1COD} - 20)}$$

DESIGN CONSIDERATIONS

It is believed that much valuable information was developed during the investigation, not only regarding theoretical concepts and their application to the actual process, but also with respect to performance parameters and operational control of the process. Table 21 compares values of the design and performance parameters for the accelerated high-rate system studied at Chino with other activated sludge processes.

The accelerated high-rate activated sludge process was characterized by extremely high loading velocities, varying from 0.2 to 3.6 (mg BOD)/(mg MLVSS)(day). The system was operated and produced high quality effluents (effluent soluble BOD ranged from 5 to 28 mg/l) and high process efficiencies (75 to 95 percent BOD removal).

The most significant finding of this investigation is that activated sludge systems can be designed to handle high organic loadings up to 3.6 (mg BOD)/(mg MLVSS)(day) with conventional gravity separators operating at an overflow rate of 13.4 $m^3/(m^2)$(day)[330 gal/(ft^2)(day)]. The capability of operating the system at the unusually low mean cell age of 0.34 day demonstrates the feasibility of utilizing the high growth-rate potential of activated sludge as a means of removing organic materials from wastewater. However, the only practical solids separation system available at present is a gravity settling unit. Research and development of improved gravity and mechanical cell separators remains an important practical need for improved biological treatment systems.

Table 21. DESIGN AND OPERATIONAL PARAMETERS FOR ACTIVATED SLUDGE PROCESSES

Parameter	Conventional activated sludge	Contact stabilization	High-rate aeration[a] (optimum)	Chino demonstration (optimum)
Mean cell age, θ_c, day	5 to 15	5 to 10	-	0.4 to 1.0
BOD loading, L_v, $\frac{\text{(mg BOD)}}{\text{(mg MLVSS)(day)}}$	0.2 to 0.5	0.2 to 0.6	1.9	2.0 to 3.5
MLVSS, mg/l	1,500 to 3,000	1,000 to 3,000 (4,000 to 10,000)[b]	2,500	600 to 1,000
Hydraulic residence time, θ, hr	4 to 8	0.3 to 0.7 (1.5 to 5)[b]	0.7	0.9
Recycle ratio	0.1 to 0.3	0.25 to 1.25	0.56	0.3 to 0.5
BOD removal efficiency, %	85 to 95	80 to 90	89	85 to 95[c]
Secondary clarifier overflow rate, $m^3/(m^2)(day)$	32.6	32.6	32.6	13.4[d]

[a]First stage performance of two-stage activated sludge plant (Reference 48).

[b]Solids stabilization unit.

[c]Soluble BOD removal efficiency.

[d]Actual operating overflow rate, no optimum rate obtained.

APPLICATION OF SYSTEM KINETICS

Inspection of the cell continuity equation (Equation 16) and Michaelis-Menten (Monod) model indicates that there is a direct relationship between substrate removal velocity, q, and mean cell age, θ_c, and between specific growth rate, or substrate (soluble BOD) removal velocity, and effluent substrate (soluble BOD) concentration, S_1. Thus, control of either q or θ_c will directly control effluent quality and process efficiency (Equation 23). Using system kinetic information and waste characteristics, an activated sludge system can be designed to produce a specified effluent quality and process efficiency.

An example of the procedure for the design of the recommended high-rate activated sludge system follows. A parallel design, using criteria for a conventional activated sludge process, is provided for comparison. Table 22 presents the design comparison between a conventional activated sludge process and high-rate activated sludge process demonstrated at Chino to treat 0.0438 m^3/sec (1 mgd) of primary settled sewage having a BOD of 200 mg/l and producing a secondary effluent BOD of 20 mg/l or less. Using the kinetic characteristics of each process and reasonable design criteria, a 382-m^3 (13,500-ft^3) aeration tank is required for the high-rate activated sludge compared to 682-m^3 (24,100-ft^3) tank for the conventional process.

Because of the present dependence upon gravity cell separation, the high-rate process requires a 685-m^3 (24,200-ft^3) secondary settling unit compared to a 283-m^3 (10,000-ft^3) unit for the conventional process. With the development of compact, high-rate mechanical cell separators and the replacement of the larger gravity settling units, a compact high-rate activated sludge plant with the potential for substantially lower overall costs could be realized.

Table 22. DESIGN COMPARISON BETWEEN CONVENTIONAL AND HIGH-RATE CHINO ACTIVATED SLUDGE PROCESSES

Design data and criteria	Conventional activated sludge plant	Demonstration activated sludge plant, Chino
F, m^3/sec	0.0438	0.0438
S_0, (mg BOD)/l	200	200
Y, $\frac{\text{(mg MLVSS produced)}}{\text{(mg BOD removed)}}$	0.5	0.92
k_d, day^{-1}	0.05	0.027
k_s, (mg BOD)/l	100	26
$\hat{q}$, $\frac{\text{(mg BOD removed)}}{\text{(mg MLVSS)(day)}}$	3.0	4.1
X_1, (mg MLVSS)/l	2,000	1,000
X_2, (mg VSS)/l	30	30
F_r, m^3/sec	0.0110	0.0219
X_r, (mg VSS)/l	7,000	4,000
a, (mg O_2)/(mg BOD removed)	0.5	0.44
bk_d, (mg O_2)/(mg MLVSS)(day)	0.1	0.43
Secondary overflow rate, $m^3/(m^2)(day)$	32.6	13.4
Effluent BOD, S_1, (mg BOD)/l	20	20
BOD removal velocity, q, $\frac{\text{(mg BOD removed)}}{\text{(mg MLVSS)(day)}}$	0.5	1.78

Table 22 (continued). DESIGN COMPARISON BETWEEN CONVENTIONAL AND HIGH-RATE CHINO ACTIVATED SLUDGE PROCESSES

Design data and criteria	Conventional activated sludge plant	Demonstration activated sludge plant, Chino
Process efficiency, E, %	90	90
L_v, $\frac{\text{(mg BOD applied)}}{\text{(mg MLVSS)(day)}}$	0.56	1.98
Mean cell age, θ_c, day	5.0	0.62
Aeration tank volume, V, m^3	682	382
Hydraulic residence time, θ, hr	4.3	2.4
Sludge wasting rate, F_w, m^3/day	22.8	127
Sludge production rate, (kg VSS)/day	272	617
Oxygen requirements, (kg O_2)/day	317	549
Secondary clarifier surface, area, m^2	116	281
Secondary clarifier volume, m^3	283	685

SECTION IX

GLOSSARY

a	Oxygen requirement per unit substrate removed
b	Oxygen requirement per unit cell oxidized
C_1	Gear reduction efficiency
C_2	Aerator motor efficiency
E	Substrate or nutrient removal efficiency
F	Influent flow rate
F_r	Return activated sludge flowrate
F_w	Waste activated sludge flowrate
k_d	Decay rate
k_t	Oxygen transfer rate
K_{COD}	Nonbiodegradable COD concentration
K_s	Half-saturation constant
L_v	Substrate loading velocity
q	Substrate or nutrient removal velocity
$\hat{q}$	Maximum substrate or nutrient removal velocity
R_f	Return sludge ratio
S_0	Influent substrate or nutrient concentration
S_1	Effluent substrate or nutrient concentration
SVI	Sludge volume index
U	Rate of oxygen consumption
V	Volume of aeration tank
X_0	Influent cell concentration
X_1	Mixed liquor cell concentration
X_2	Effluent cell concentration
X_r	Return activated sludge cell concentration
X_w	Waste activated sludge cell concentration
Y	Yield coefficient
Y_n	Net yield coefficient
μ	Specific growth rate
$\hat{\mu}$	Maximum specific growth rate
θ	Hydraulic residence time
θ_c	Mean cell age

SECTION X

REFERENCES

1. Michaelis, L., and Menten, M.L., "Die Kinetik der Invertinwirkung," Biochem. Z., 49, p. 333, 1913

2. Monod, J., Recherces sur la Croissances des Cultures Bacteriennes, Paris, Hermann and Cie, 1942

3. Monod, J., "The Growth of Bacterial Cultures," Ann. Rev. Microbiol., 3, p. 371, 1949

4. Pearson, E.A. The Case for Continuous Flow (Chemostat) Kinetic Descriptions of Plankton - Nutrient Growth Relationships in Eutrophication Analyses, Prepared for Joint Industry Government Committee Meeting on Algae Growth Potential, Chicago, Illinois, 1968

5. Fencl, Z., "Theoretical Analysis of Continuous Culture Systems," In: Theoretical and Methodological Basis for Continuous Culture of Microorganisms, Ed. I. Malek and Z. Fencl, Academic Press, New York, 1966

6. Stewart, M.J., Reaction Kinetics and Operational Parameters of Continuous Flow Anaerobic Fermentation Processes, SERL Publication No. 4, IER Series 90, University of California, Berkeley, 1958

7. Toerien, D.F., Huang, C.H., Radimsky, J., Pearson, E.A. and Scherfig, J. Final Report - Provisional Algal Assay Procedures, SERL Report No. 71-6, Sanitary Engineering Research Laboratory, Univ. of California, Berkeley, 1971

8. Andrews, J.F., Cole, R.D., and Pearson, E.A., Kinetics and Characteristics of Multistage Methane Fermentations, SERL Report No. 64-11, University of California, Berkeley, 1964

9. McCabe, B.J., and Eckenfelder, W.W., "BOD Removal and Sludge Growth in the Activated Sludge Process," J. Water Pollution Control Federation, 33, 258-271, 1961

10. Wilson, I.S., "Concentration Effects in the Biological Oxidation of Trade Wastes" Proc. 1st Intern. Conf. Water Pollution Research, London, Pergamon Press, 1962

11. Rich, L.G., Unit Operations of Sanitary Engineering, New York, John Wiley and Sons, 1961

12. Eckenfelder, W.W., and McCabe, B.J., "Advances in Biological Waste Treatment," Proc. of the 3rd Conference on Biological Waste Treatment. Pergamon Press, 1963

13. Lawrence, A.W., and P.L. McCarty, Kinetics of Methane Fermentation in Anaerobic Waste Treatment, Dept. of Civil Engineering, Stanford Univ., 196

14. Agardy, F.J., Cole, R.D., and Pearson, E.A., Kinetic and Activity Parameters of Anaerobic Fermentation Systems, First Annual Report, Berkeley: Sanit. Eng. Research Lab., Univ. of Calif., 1963

15. Metcalf and Eddy, Inc., Wastewater Engineering: Collection, Treatment, Disposal, McGraw-Hill Series in Water Resources and Environmental Engineering, 1925

16. Standard Methods for the Examination of Water and Wastewater, 13th Ed., American Public Health Association, AWWA, WPCF, New York, N.Y., 1971

17. FWPCA Methods for Chemical Analysis of Water and Wastes, FWPCA, Division of Water Quality Research Analytical Quality Control Laboratory, Cincinnati Ohio, 1969

18. Patterson, J.W., Brezonik, P.L., and Putnam, H.D., "Measurement and Significance of Adenosine Triphosphate in Activated Sludge," Environmental Science and Technology, Vol. A, 1970

19. Beutler, E., and Baluda, M.C., "Simplified Determination of Blood Adenosine Triphosphate Using the Firefly System," Blood, Vol. 23, 1964

20. Baer, R.M., "Computer Program COMMON G2 CAL NLIN, Nonlinear Regression," Computer Center, University of California, Berkeley, 1967.

21. Patterson, J.W., Brezonik, P.L., and Putnam, H.D., "Sludge Activity Parameters and Their Application to Toxicity Measurements in Activated Sludge," Paper presented at the 24th Industrial Waste Conference, Purdue Univ., 1969

22. Ford, D.L., Eckenfelder, W.W., and Yang, T., "Dehydrogenase Enzyme as a Parameter of Activated Sludge Activities," Proc. 21st Annual Industrial Waste Conference, Purdue Univ., 1966

23. Eckhoff, D.W., and Jenkins, D., Activated Sludge Systems; Kinetics of the Steady and Transient States, SERL Report No. 67-12, Sanitary Engineering Research Laboratory, Univ. of Calif., Berkeley, 1967

24. Hopwood, A.P., and Downing, A.L., "Factors Affecting the Rate of Production and Properties of Activated Sludge in Plants Treating Domestic Sewage," J. Indust. Sewage Purification, Part 5, 1965

25. Jenkins, D., and Menar, A.B., The Fate of Phosphorus in Sewage Treatment Processes; Part 1, Primary Sedimentation and Activated Sludge, SERL Report 67-6, Sanitary Engineering Research Laboratory, Univ. of Calif., Berkeley, 1967

26. Heukelekian, H., Orford, H.E., and Manganelli, R., "Factors Affecting the Quantity of Sludge Production in the Activated Sludge Process," Sew. and Industrial Wastes, 23, 945, 1951

27. Shea, T.G., W.A. Pretorius, R.D. Cole, and E.A. Pearson, Kinetics of Hydrogen Assimilation in Methane Fermentation, SERL Report No. 68-7, Sanitary Engineering Research Laboratory, Univ. of Calif., Berkeley, 1968

28. Middlebrooks, E.J., Jenkins, D., Neal, J., and Phillips, J., "Kinetics and Effluent Quality in Extended Aeration," Water Research, 3, 39, 1969

29. Stewart, M.J., and Ludwig, H.F., "Theory of the MAS Waste-water Treatment Process," Water and Sewage Works, 109, 97, 1962

30. Gram, A.L., Reaction Kinetics of Aerobic Biological Processes. Sanitary Engineering Research Laboratory, University of California, Berkeley, No. 2, IER Series 90, 1956

31. Beneder, P., and Horvath, T., "A Practical Approach to Activated Sludge Kinetics," Water Research, 1, 1967

32. Pearson, E.A., and Haas, P., Kinetics Analysis of Whittier Narrows Water Reclamation Plant, Report to Los Angeles County Sanitation Districts, 1967

33. Stack, V.T. and Conway, R.A., "Design Data for Completely-Mixed Activated Sludge Treatment," Sew. and Ind. Wastes, 31, No. 10, 1959

34. Servici, J.A. and Bogan, R.H., "Free Energy as a Parameter in Biological Treatment," Proc. ASCE, 89, S.A. 3, pp. 17-40 1963

35. McWhorter, T.R., and Heukelekian, H., "Growth and Endogenous Phases in the Oxidation of Glucose," Proc. Intl. Conf. on Water Pollution Research, Vol. 2, pp. 419-345, Pergamon Press 1962

36. Dryden, F.E., Barrett, P.H., Kissinger, J.C., and Eckenfelder, W.W., "Treatment of Fine Chemical Wastes by High-Rate Activated Sludge," Proc. 9th Purdue Industrial Waste Conference, Purdue University, Lafayette, Indiana 1954

37. Hazeltine, T.R., Some Recent Advances in the Design of Activated Sludge Systems. Pre-publication Manuscript presented at the Annual meeting of the Calif. Water Pollution Cont. Fed., Sacramento, California 1962

38. Jenkins, D., and Garrison, W.M., "Control of Activated Sludge by Mean Cell Residence Time," JWPCF 40, 1965, 1968

39. EIMCO Research and Development Center, EIMCO-SIMCO Aerator, Palatine, Illinois

40. Downing, A.L., Tomlinson, T.G. and Truesdale, G.A., Effect of Inhibitions on Nitrification in the Activated Sludge Process, 1961

41. Pearson, E.A., "Kinetics of Biological Treatment," Presented at Special Lecture Series, Advances in Water Quality Improvement, University of Texas, Austin, Texas 1966

42. McKinney, R.E., "Biological Oxidation of Organic Matter," in Advances in Biological Waste Treatment, W.W. Eckenfelder, Jr. and J. McCabe, eds., 1960

43. McKinney, R.E. and Horwood, M.P., "Fundamental Approach to the Activated Sludge Process. I., Floc Producing Bacteria," Sewage and Industrial Wastes, 24, 117, 1952

44. Greenberg, A.E., Klein, G., and Kaufman, W.J., "The Effect of Phosphorus on the Activated Sludge Process," Sewage and Industrial Wastes, 27, 1955

45. Helmers, E.N., et al., "Nutritional Requirements in the Biological Stabilization of Industrial Wastes. III, Treatment with Supplementary Nutrients," Sewage and Industrial Wastes, 24, 1952

46. Simpson, R.W., "Activated Sludge Modification," Water and Sewage Works, 106, 421-426, 1959

SECTION XI

APPENDIX

NONSTANDARD ANALYTICAL METHODS

ADENOSINE TRIPHOSPHATE

The emission of light by fireflies is known as bioluminescence and is an energetic reaction deriving energy from the hydrolysis of ATP to ADP and inorganic phosphate. The amount of light produced by firefly extract is directly proportional to the amount of ATP added. The reaction involves the enzyme luciferase, the bioluminescent compound luciferin, and ATP. Luciferin and ATP react in the presence of luciferase and magnesium ions to form an enzyme luciferine adenosine monophosphate complex and inorganic phosphate. The complex is oxidized to oxyluciferyl-adenylate, followed by the release of a quantum of light. In the presence of an arsenate buffer, there is an initial burst of luminescence followed by an intermediate level of light emission that decays steadily with time.

Procedure

(1) A 10-ml sample is added to 40 ml of Tris buffer in a 50-ml volumetric flask.

(2) The ATP is extracted by immediately placing the solution in a boiling water bath for 15 minutes and then transferring it to an ice bath for cooling.

(3) The volume of the sample is restored to 50 ml and the particulate matter is removed by centrifugation or filtration.

(4) 2 ml of ATP extract is added to 2 ml of firefly extract. The mixture is mixed by shaking it for 15 seconds and at exactly two minutes the light emission is measured using a Turner Fluorometer.

DEHYDROGENASE ACTIVITY

Triphenyl tetrazolium chloride (TTC) is reduced to Triphenyl formazan (TF) in the presence of dehydrogenase. The TCC is colorless while the TF has a red color. The intensity of the red color produced is proportional to the dehydrogenase activity.

Procedure

(1) Measure off the homogenized sample aliquot 8 ml and place it in a test tube together with 1 ml of 0.05 M Tris-HCl buffer.

(2) Bubble nitrogen gas through the sample to remove any oxygen.

(3) Place sample in a preheated 37°C waterbath and add 1 ml of the TTC-glucose reagent. Let the reaction occur for 60 minutes.

(4) At the end of 60 minutes, stop the color development by adding 1 ml of formaldehyde.

(5) Dilute sample with 95 percent ethanol to 50 ml, mix well, and centrifuge the sample.

(6) Measure the percent transmission of the TF extract in a spectrophotometer at a wavelength of 483 mμ.